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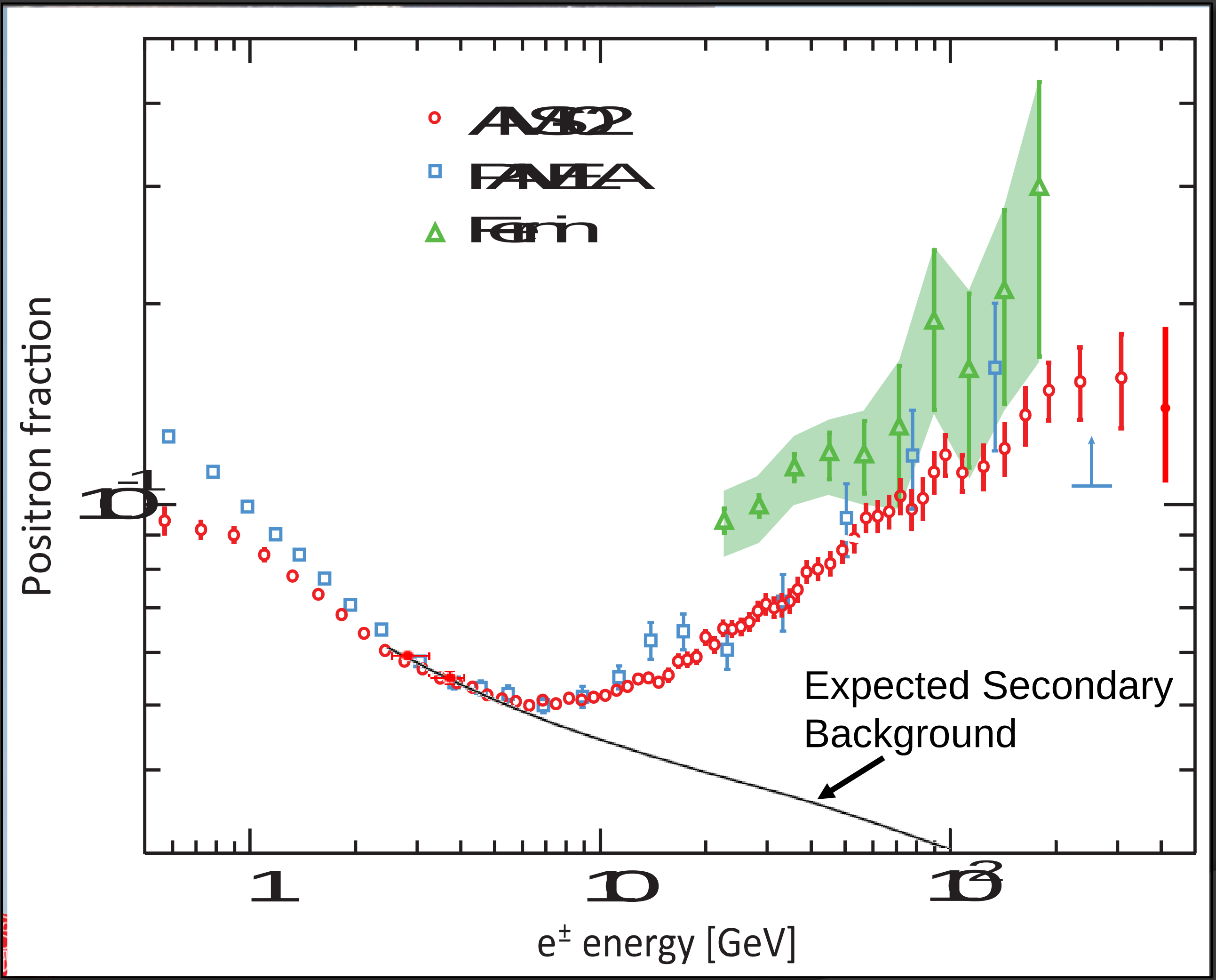
Indirect Searches for Dark Matter: Excesses and Anomalies

A Number of Unexplained or Ambiguous Observations Persist:

- Excess 511 keV emission from Galactic Bulge (INTEGRAL)
- Excess high-energy cosmic ray positrons (PAMELA, AMS)
- Excess isotropic radio emission (ARCADE, etc.)
- 130 GeV line from the Galactic Center (Fermi)
- 3.5 keV line from Galaxy Clusters (XMM-Newton, Chandra)
- Excess GeV emission from the Galactic Center (Fermi)

Any of these signals could plausibly be the result of annihilating/decaying dark matter particles (although most probably are not)

The Cosmic Ray Positron Excess

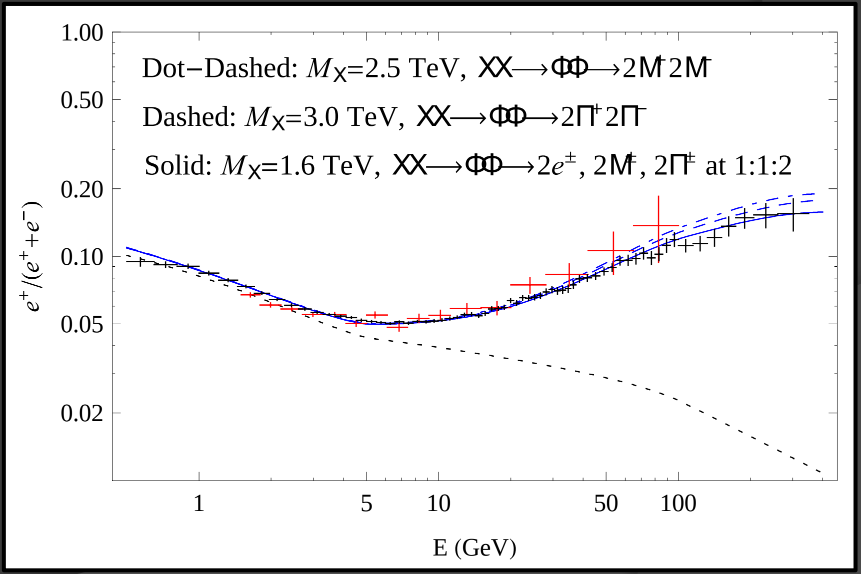


Expected Secondary Background

Rise above ~10 GeV indicates the presence of a primary source of highly energetic cosmic ray positrons

The Cosmic Ray Positron Excess

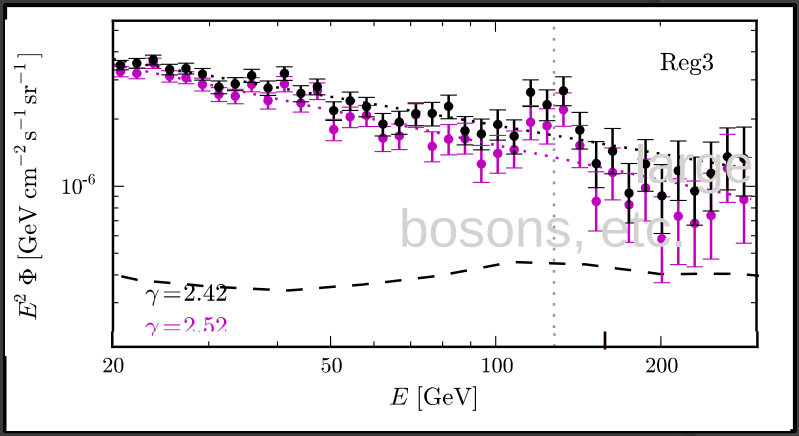
- These measurements strongly favor the existence of a nearby (~kpc) source(s) of very high energy (~0.1-1 TeV) cosmic ray positrons
- Dark matter particles could be responsible, but require:
  1) Annihilations must produce mostly muons, electrons
  2) Very high annihilation rates (Sommerfeld? Non-thermal?)
  3) Cored profile for the Milky Way (to evade gamma-ray constraints)
- Nearby pulsars could also do the job (from the perspective of Occam's Razor, this is where my money is)
- Future measurements from AMS may help to clarify this situation

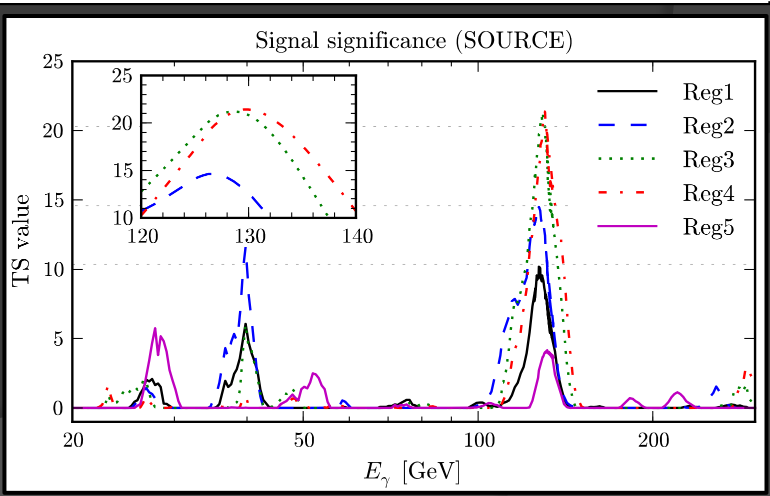


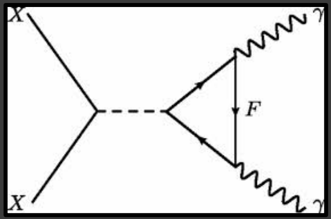
Cholis and Hooper, PRD, arXiv:1304.1840

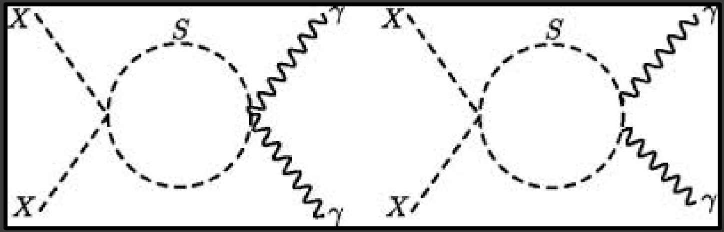
The 130 GeV Line

- In 2012, Christoph Weniger and collaborators identified a fairly significant (~4σ) line-like feature in the publically available Fermi data, spatially consistent with dark matter annihilating in the Milky Way's halo
- Requires the dark matter to annihilate with a large cross section to γγ, γZ, and/or γh final states, and without large cross sections to quarks, gauge bosons, etc.



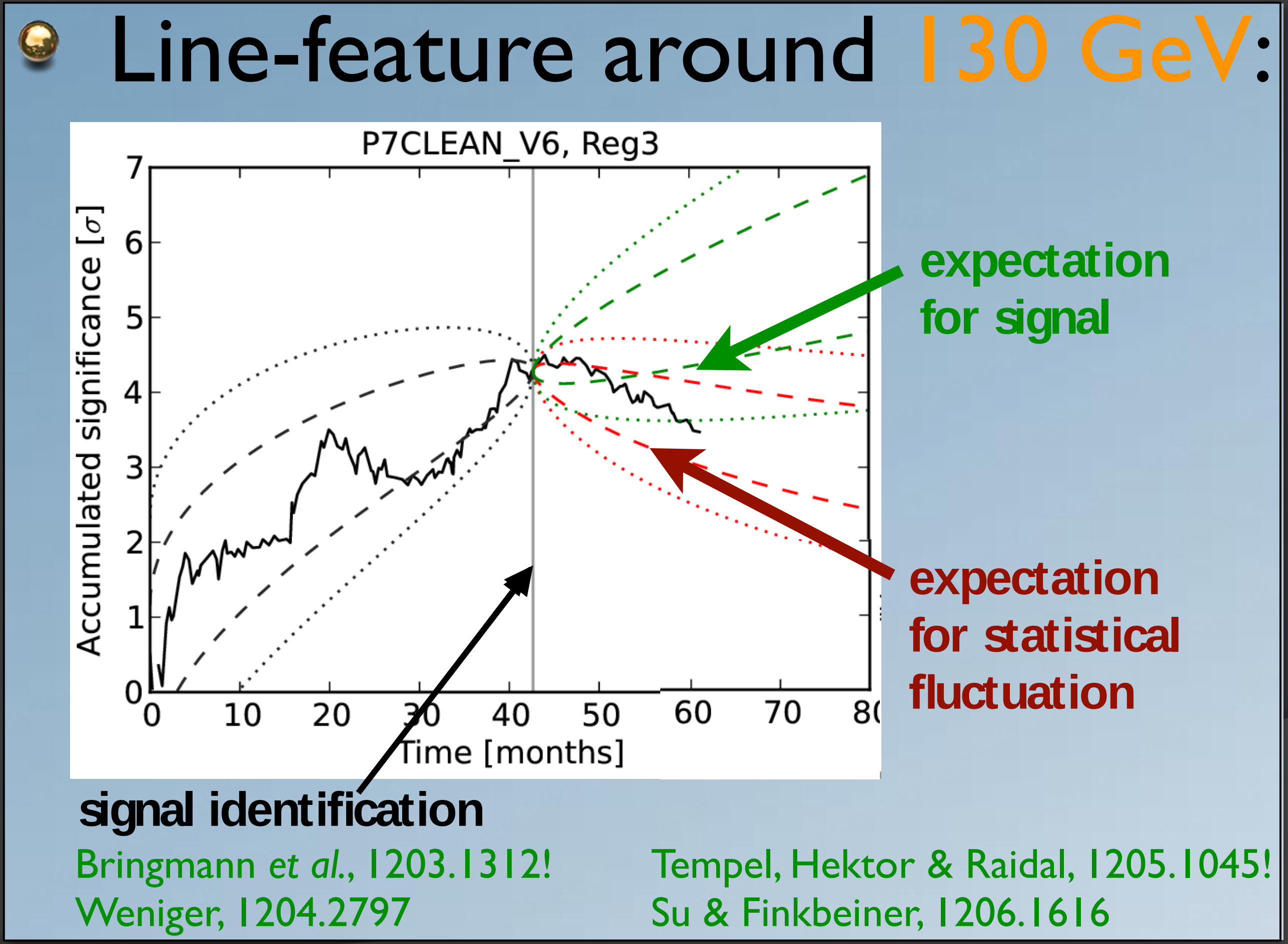






The 130 GeV Line

- Since the line’s identification, its statistical significance has decreased
- Perhaps this was nothing more than a statistical fluke?



- Line-feature around 130 GeV:

expectation for signal

expectation for statistical fluctuation

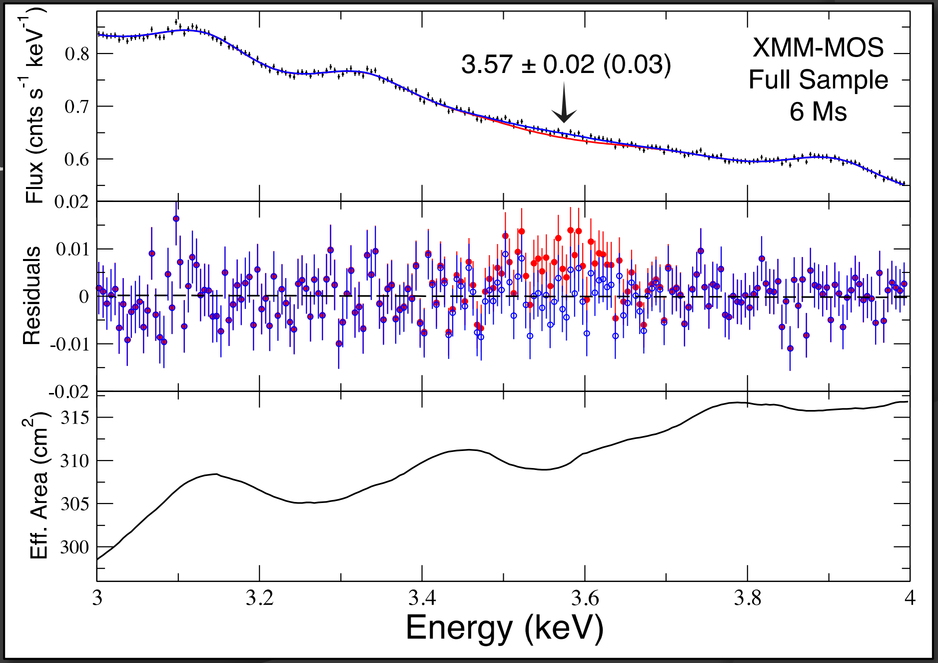
signal identification

Bringmann *et al.*, 1203.1312!
Weniger, 1204.2797

Tempel, Hektor & Raidal, 1205.1045!
Su & Finkbeiner, 1206.1616

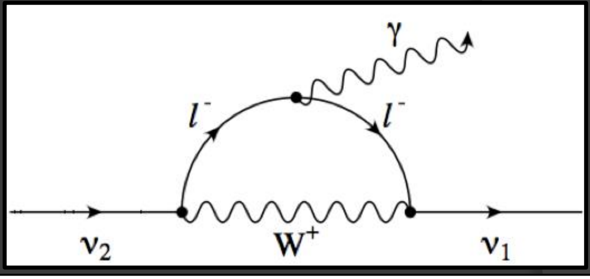
The X-Ray Line

- Earlier this year, two groups reported the observation of an unexpected X-ray line at ~3.56 keV
- Bulbul et al. reported the detection of this line from a stacked sample of 73 galaxy clusters with XMM-Newton (~4-5σ) and from the Perseus Cluster with Chandra
- Shortly thereafter, Boyarsky et al. reported the detection of a similar line from the Andromeda Gala and from the outskirts of the Perseus Cluster using XMM-Newton)
- Possibly an unknown atomic transition line? (hard to access)

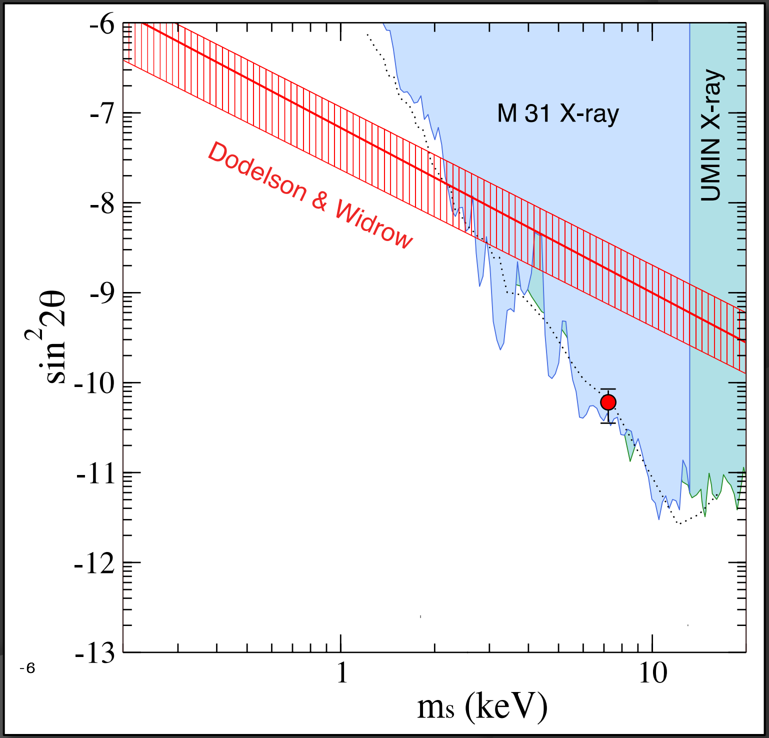


The X-Ray Line

- Among other possibilities, such a line could result from the decays of a ~7 keV sterile neutrino
- Such particles could be produced in the early universe via oscillations with active neutrinos (Dodelson-Widrow mechanism)

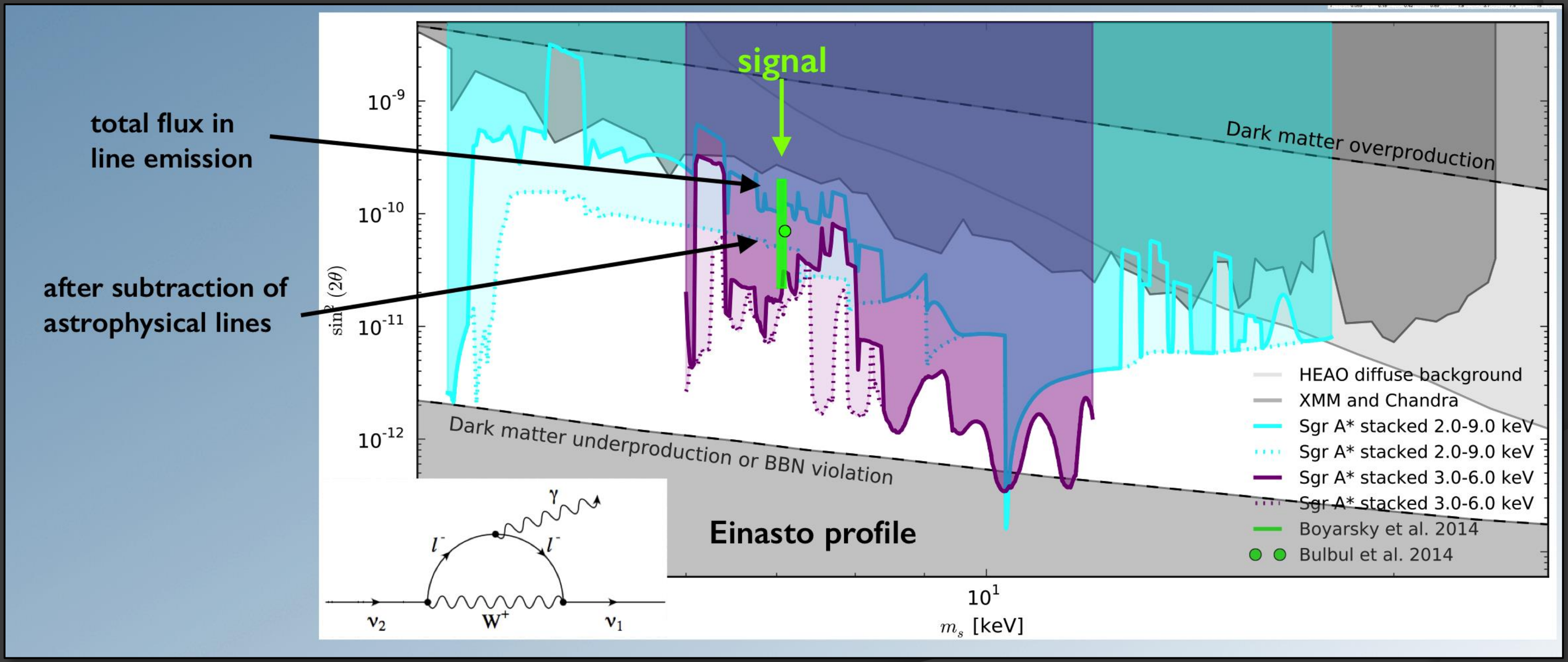


- In simple models, a 7 keV sterile neutrino that made up all of the dark matter would produce a line that is much brighter than is observed; In contrast, the observed line might come from a sterile neutrino that makes up ~1% of the dark matter
- Alternatively, the sterile neutrino could be part of a sector with a large lepton number asymmetry or other features that enhance their production and abundance



The X-Ray Line

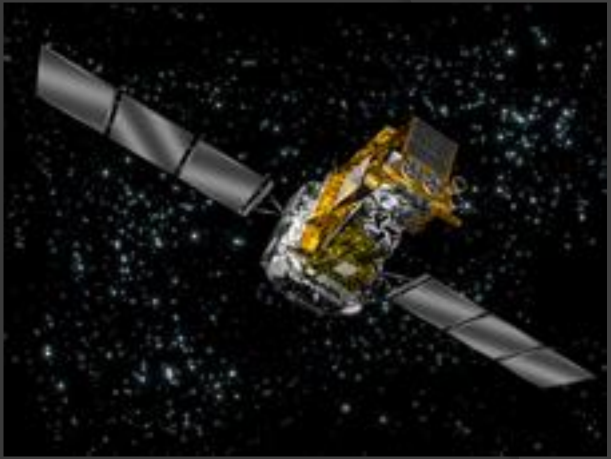
- To me, the elephant in the room is the question of why no such line is observed from the halo of the Milky Way
- Velocity dependent emission is one way around this constraint (eXciting dark matter, for example; see 1402.6671)

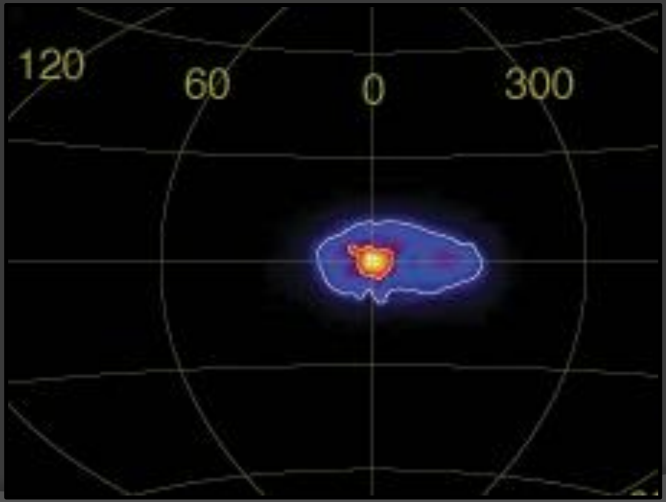


Riemer-Sorensen, 1405.7943

The 511 keV Line

- In 2004, the INTEGRAL satellite observed a bright 511 keV signal from the region of the Galactic Bulge
- Consistent with the annihilations (or decays) of ~MeV dark matter particles
- More recent observations by INTEGRAL revealed this signal to be somewhat asymmetric, similar to the observed distribution of low-mass X-ray binaries





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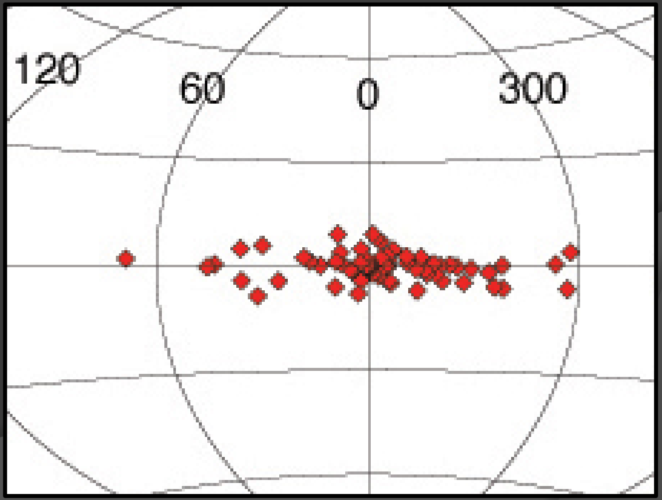
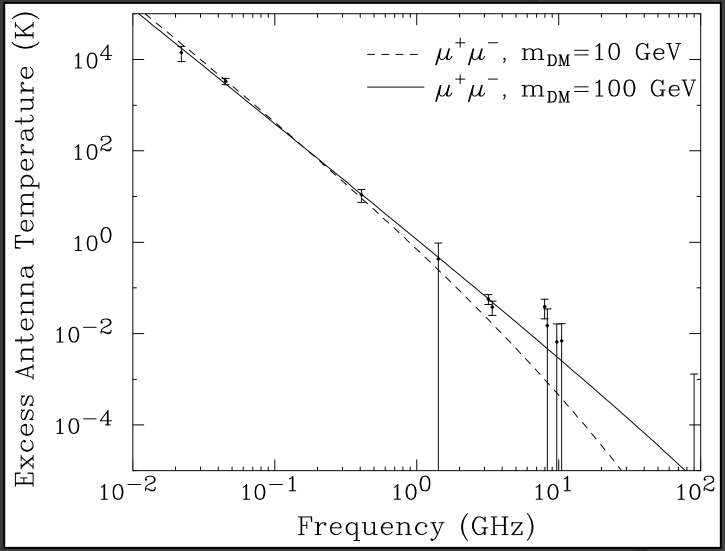


The Isotropic Radio Background

- Several radio telescopes, including ARCADE 2, have reported an isotropic background that is ~5-6 times higher than predicted from astrophysical sources
- It has been suggested that this might be synchrotron emission from dark matter annihilation products (Fornengo et al 2011/2014, Hooper et al 2012)
- Probably requires dark matter that annihilates mostly to leptons, and with a fairly large cross section – some tension with gamma-ray and positron constraints
- Interest in this possibility continues, largely due to how difficult it is to explain this observation with plausible astrophysics (for example, Holder 1207.0856, Cline and Vincent 1210.2717)



Excesses and Anomalies (circa 2014)

Anomaly	**Info. Content**	**Astrophysics?**	**Dark Matter?**
511 keV Radio Bkg. Positron Excess 130 GeV line 3.5 keV line GeV Excess			

Excesses and Anomalies (circa 2014)

Anomaly	**Info. Content**	**Astrophysics?**	**Dark Matter?**
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3.5 keV line			
GeV Excess			

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130 GeV line	Low significance	NA	Non-standard, plausible
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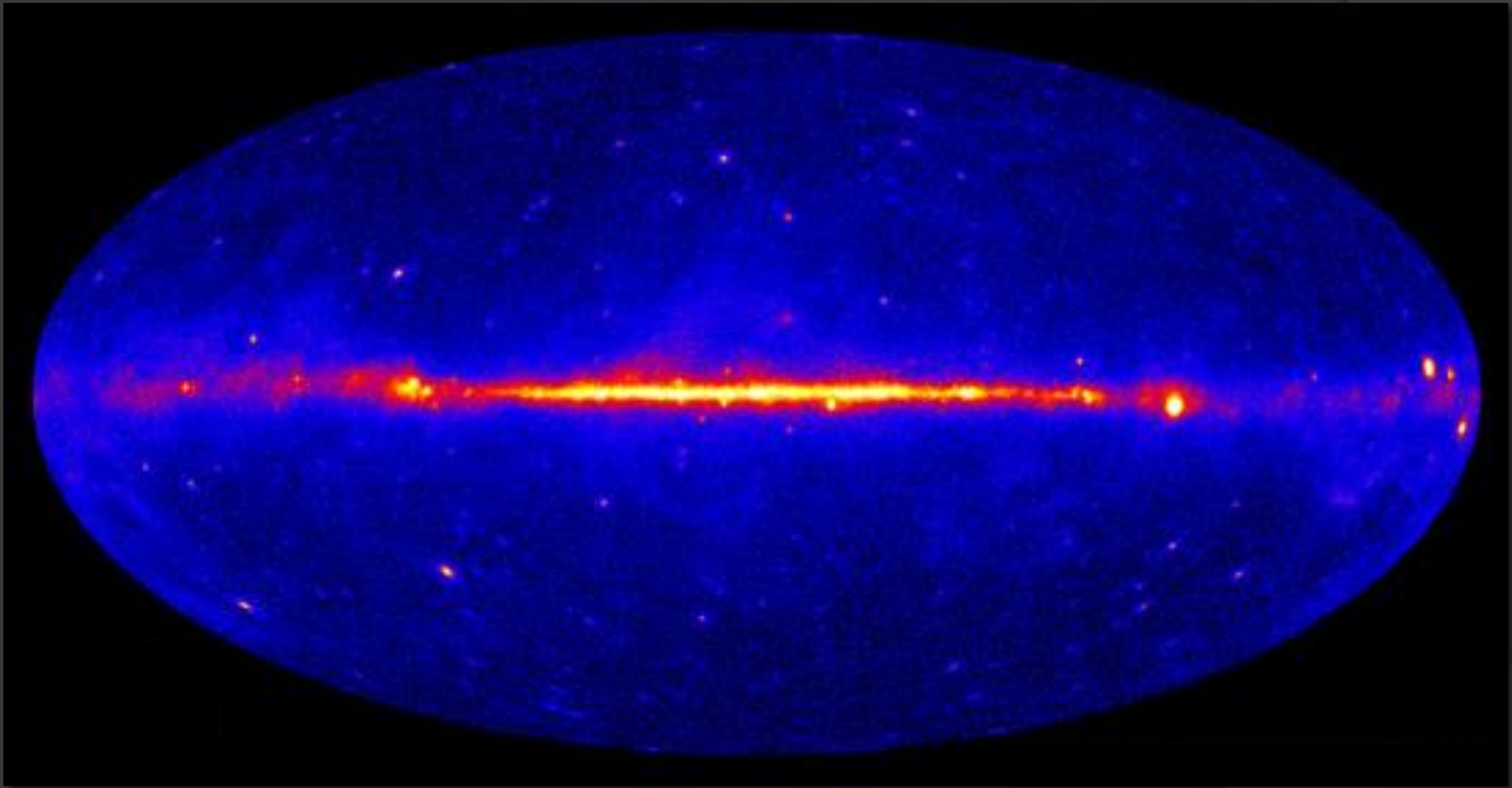
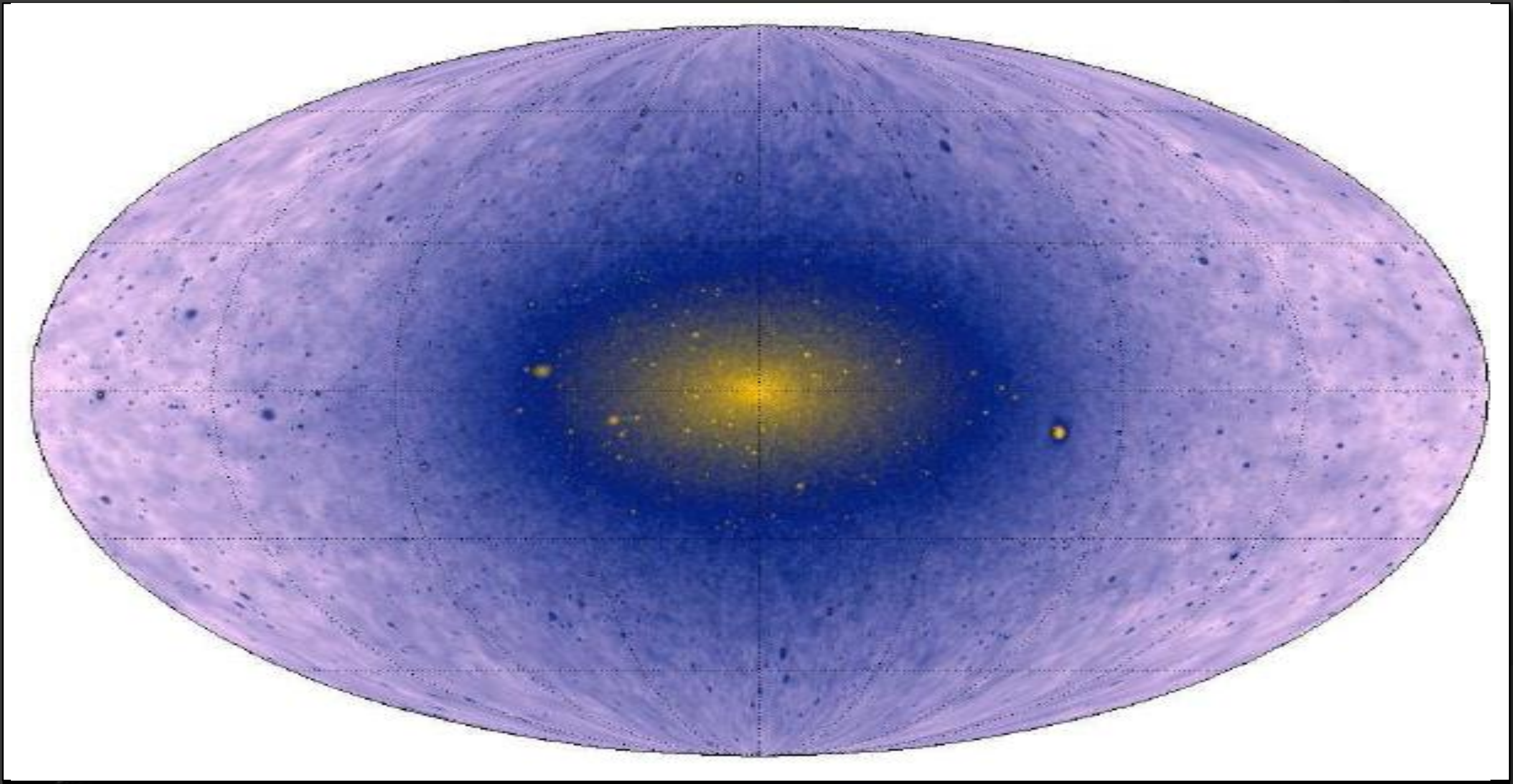
GeV Excess	High	None apparent	Standard

Caveat: Every entry in this table is highly subjective
Advice: Learn the details for yourself and make your own evaluations





The Signal:
Gamma Rays from Dark Matter Annihilations

The gamma-ray signal from dark matter annihilations is described by:

$$\Phi_\gamma(E_\gamma,\psi) = \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\frac{\langle\sigma v\rangle}{8\pi m_X^2}\int_{\mathrm{los}}\rho^2(r)\mathrm{d}l$$

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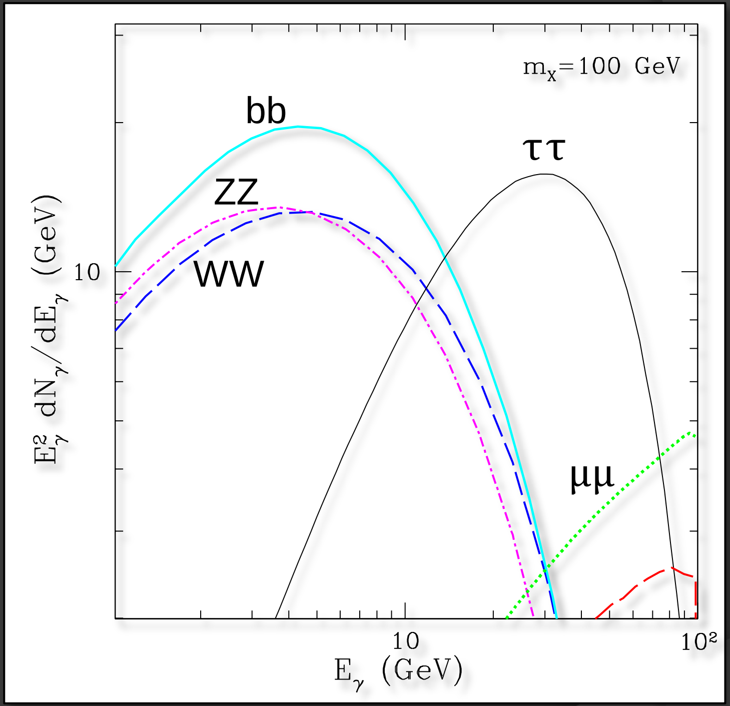

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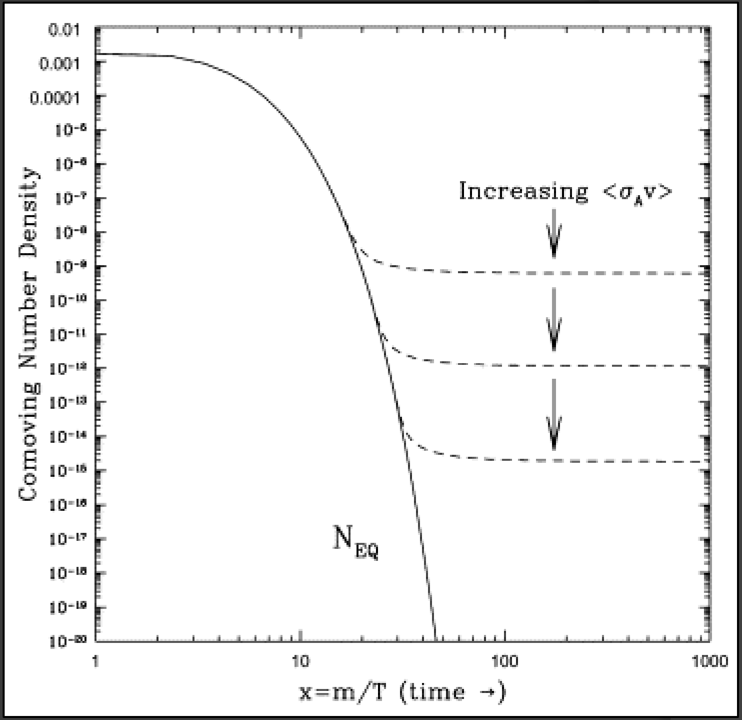

1) Distinctive “bump-like” spectrum

2) Normalization of the signal is set by the dark matter’s mass and annihilation cross section (in the low-velocity limit)

-To be produced with the observed dark matter abundance, a GeV-TeV thermal relic must annihilate at a rate equivalent to $\sigma v \sim 2\times10^{-26}$ cm^3/s (at freeze-out)

-Although many model-dependent factors can lead to a somewhat different annihilation cross section today (velocity dependence, co-annihilations, resonances), most models predict current annihilation rates that are not far from $\sim 10^{-26}$ cm^3/s

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Gamma Rays from Dark Matter Annihilations

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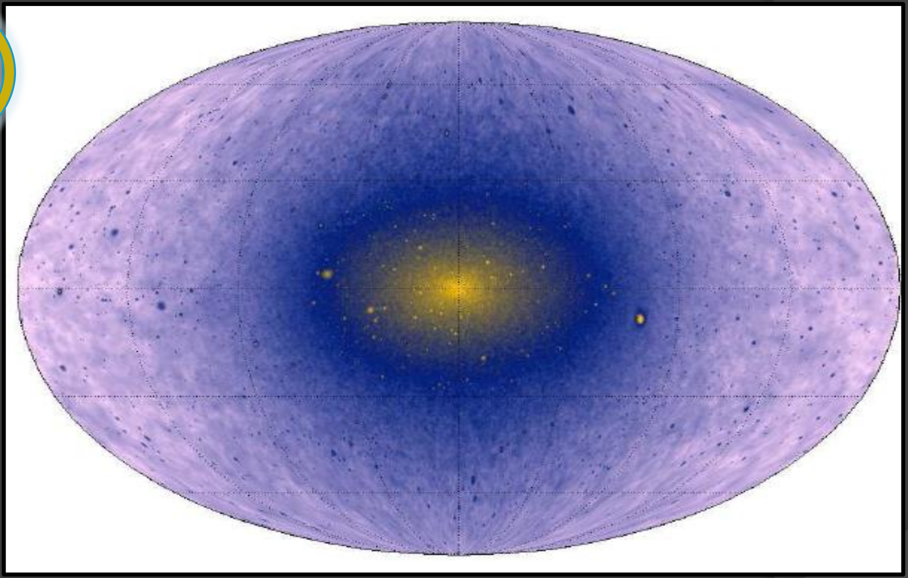


M. Kuhlen *et al*.

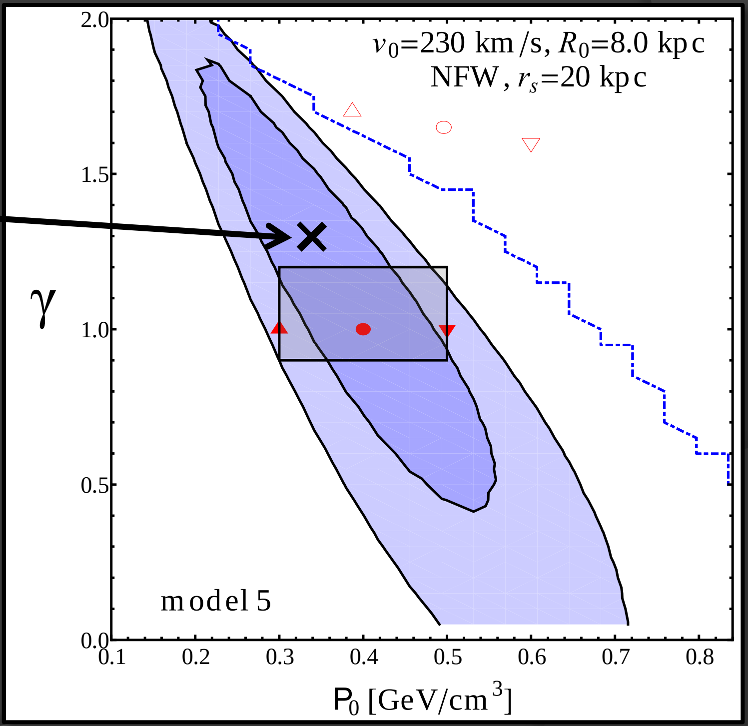
1) Distinctive “bump-like” spectrum

2) Normalization of the signal is set by the dark matter’s mass and annihilation cross section (in the low-velocity limit)

3) Signal concentrated around the Galactic Center (but not point-like) with approximate spherical symmetry; precise morphology determined by the dark matter distribution

The Distribution of Dark Matter in the Inner Milky Way

- Dark matter only simulations (Via Lactea, Aquarius, etc.) produce halos that possess inner profiles of $\rho \alpha r^{-\gamma}$ where $\gamma \sim 1.0$ to 1.2
- The inner volume (~10 kpc) of the Milky Way is dominated by baryons, not dark matter – significant departures from the results of dark matter-only simulations may be expected
- Existing microlensing and dynamical data are not capable of determining the inner slope, although $\gamma \sim 1.3$ provides the best fit
- Although hydrodynamical simulations have begun to converge in favor of a moderate degree of contraction in Milky Way-like halos (favoring $\gamma \sim 1.2$-1.5), other groups find that cusps may be flattened if baryonic feedback processes are very efficient ($\gamma < 1$)
- We keep an open mind and adopt a generalized profile with an inner slope, γ



Iocco, et al., arXiv:1107.5810;
Gnedin, et al., arXiv:1108.5736

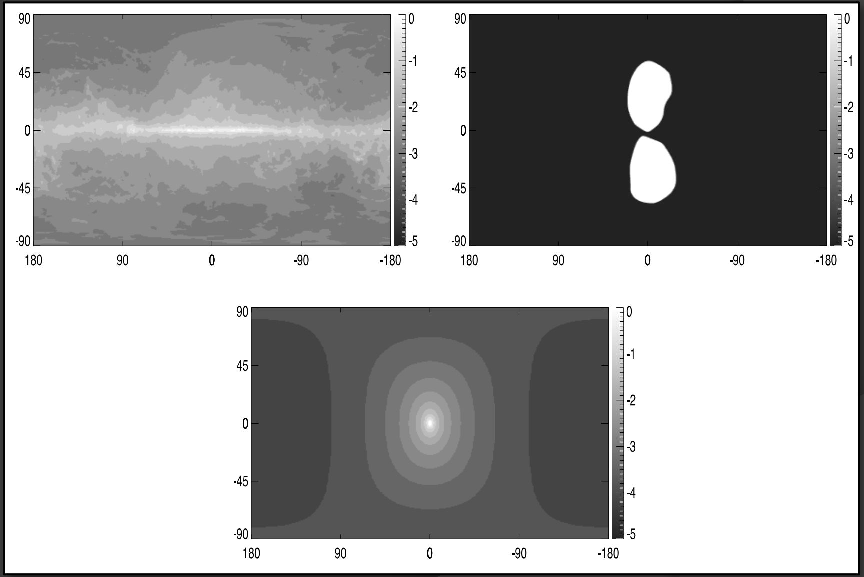
Basic Analysis Approach

1) Inner Galaxy Analysis:

Sum spatial templates (diffuse+bubbles+isotropic+dark matter), and constrain the intensity of each component independently in each energy bin across the entire sky (except within 1° of the plane or within 2° of bright sources)

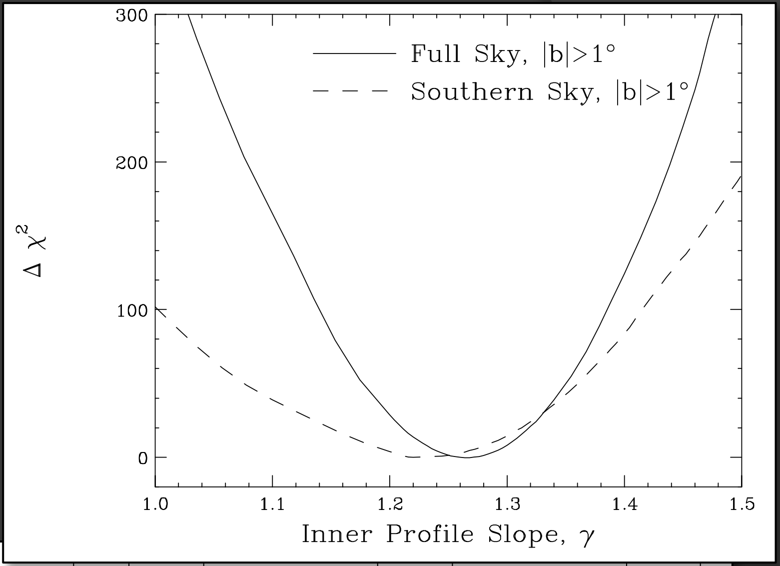
2) Galactic Center Analysis:

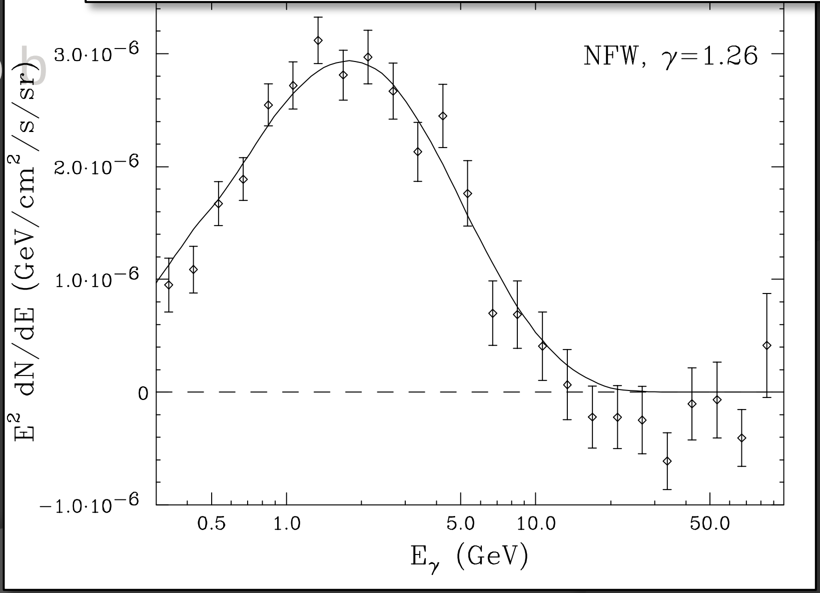
In the inner 10°x10° box around the GC, fit the data to the sum of the diffuse model, all known point sources, 20 cm template, isotropic template, and dark matter

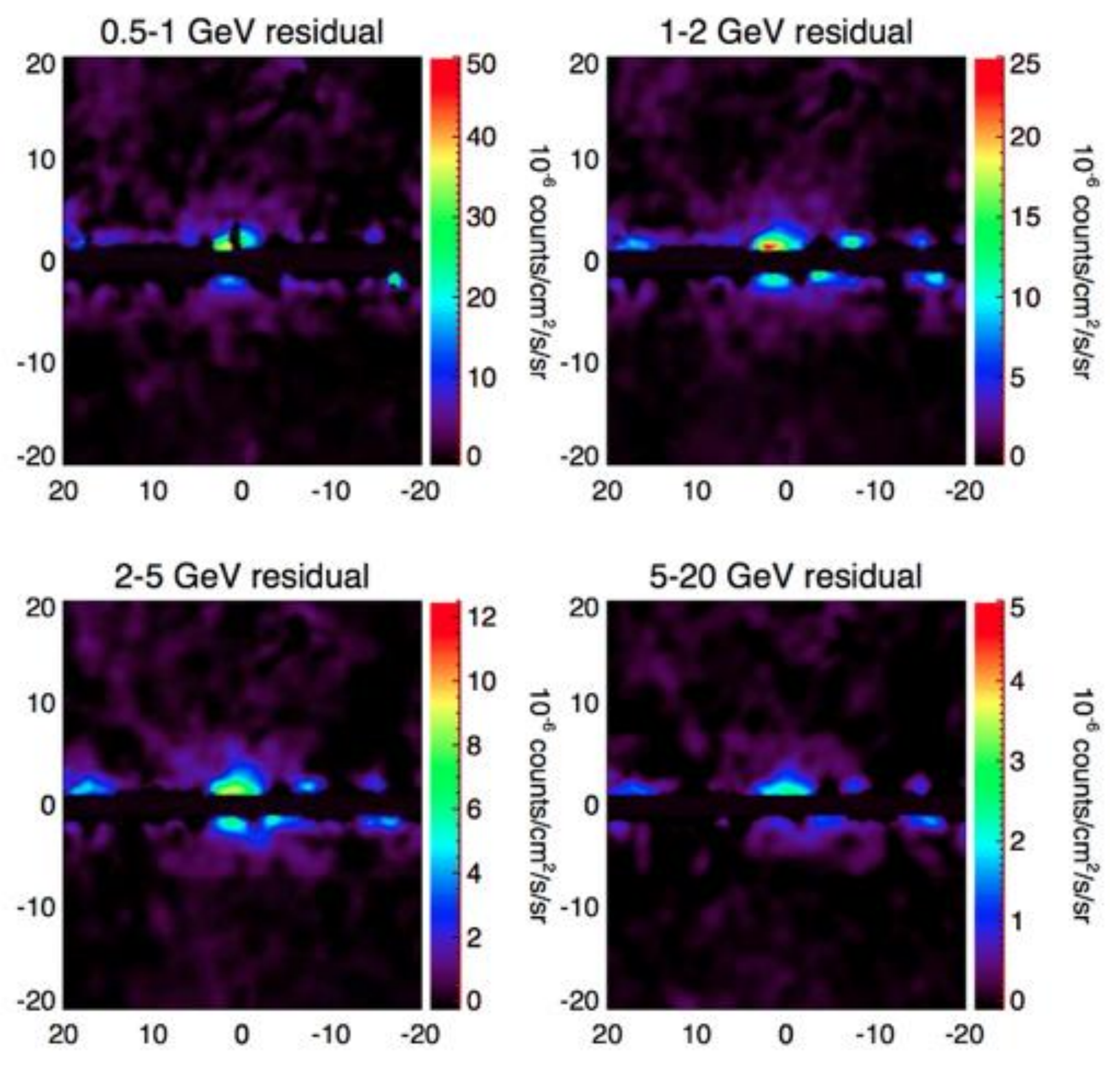


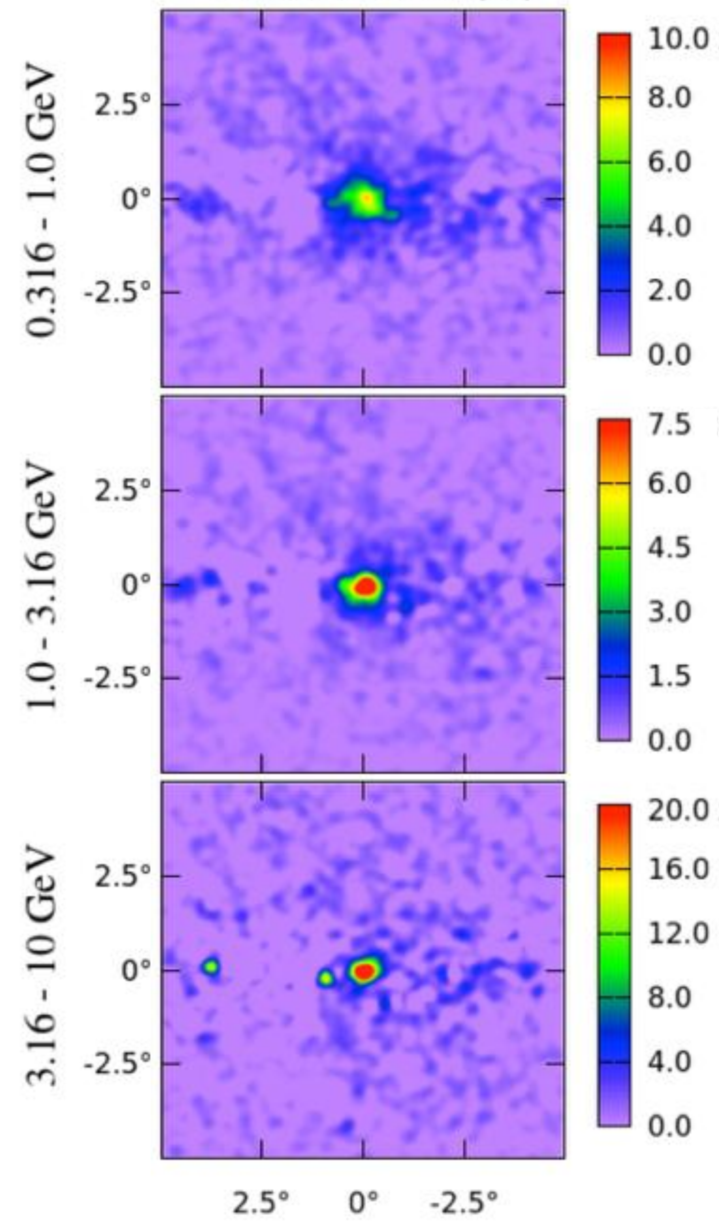
Basic Features of the GeV Excess

- The excess is distributed around the Galactic Center with a flux that falls off approximately as $r^{-2.5}$ (if interpreted as dark matter annihilation products, this implies $\rho_{DM} \sim r^{-1.25}$)
- The spectrum of this excess peaks at ~1-3 GeV, and is in very good agreement with that predicted from a 30-40 GeV WIMP (annihilating to b quarks)
- To normalize the observed signal with annihilating dark matter, a cross section of $\sigma v \sim 2 \times 10^{-26}$ cm^3/s is required (for $\rho_{local} = 0.3$ GeV/cm^3)






0.5-1 GeV residual
1-2 GeV residual
2-5 GeV residual
5-20 GeV residual
20
10
0
-10
-20
50
40
30
20
10
0
25
20
15
10
5
0
12
10
8
6
4
2
0
5
4
3
2
1
0
10^-6 counts/cm^2/s/sr


0.316 - 1.0 GeV
1.0 - 3.16 GeV
3.16 - 10 GeV
2.5°
0°
-2.5°
10.0
8.0
6.0
4.0
2.0
0.0
7.5
6.0
4.5
3.0
1.5
0.0
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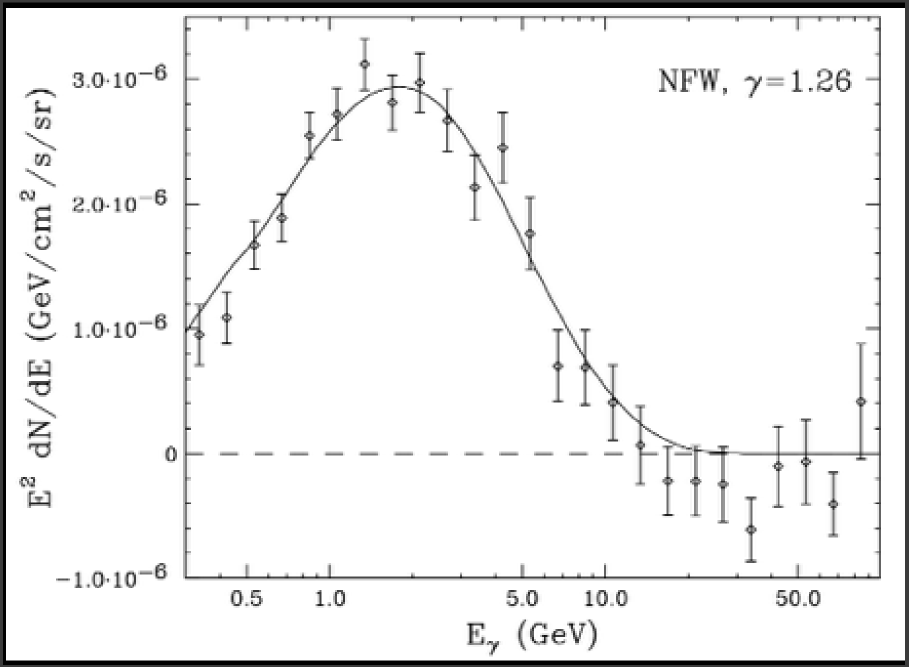
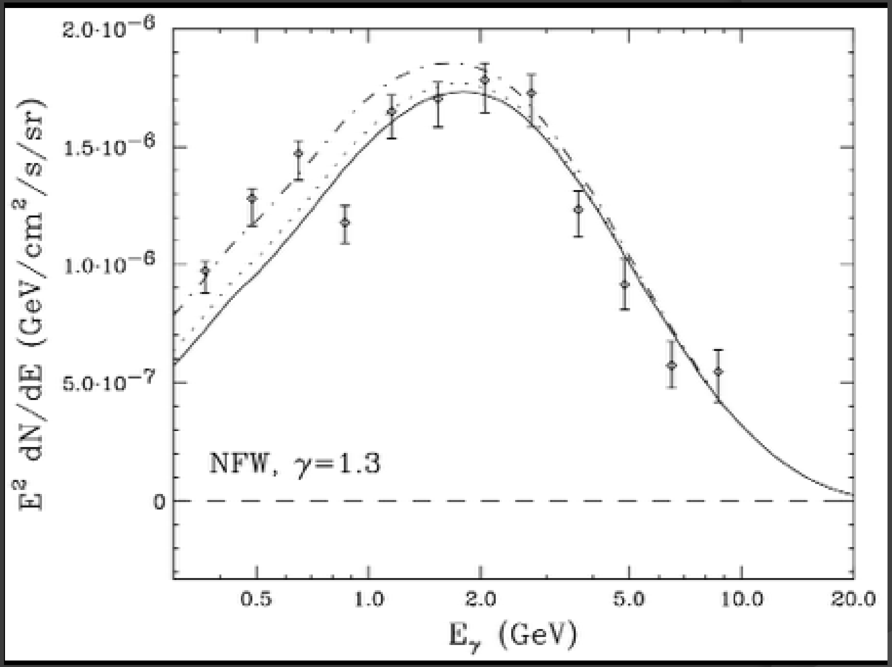
16.0
12.0
8.0
4.0
0.0


NFW, γ=1.26
E^2 dN/dE (GeV/cm^2/s/sr)
3.0·10^{-6}
2.0·10^{-6}
1.0·10^{-6}
0
−1.0·10^{-6}
0.5
1.0
5.0
10.0
50.0
E_γ (GeV)


2.0·10^{-6}
1.5·10^{-6}
1.0·10^{-6}
5.0·10^{-7}
0
NFW, γ=1.3
E^2 dN/dE (GeV/cm^2/s/sr)
0.5
1.0
2.0
5.0
10.0
20.0
E_γ (GeV)

For More Details:

T. Daylan, D. Finkbeiner, DH, T. Linden, S. Portillo, N. Rodd, and T. Slatyer, arXiv:1402.6703 (submitted to PRD)

For earlier work related to this signal and its interpretation, see:

- L. Goodenough, DH, arXiv:0910.2998
- DH, L. Goodenough, PLB, arXiv:1010.2752
- DH, T. Linden, PRD, arXiv:1110.0006
- K. Abazajian, M. Kaplinghat, PRD, arXiv:1207.6047
- DH, T. Slatyer, PDU, arXiv:1302.6589
- C. Gordon, O. Macias, PRD, arXiv:1306.5725
- W. Huang, A. Urbano, W. Xue, arXiv:1307.6862
- K. Abazajian, N. Canac, S.Horiuchi, M. Kaplinghat, arXiv:1402.4090

As far as I am aware, no published analysis of this data has disagreed with these conclusions – the signal is there, and it has the basic features described on the previous slides

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In the remainder of this talk, I am going to skip over many details and questions, and focus on four main points

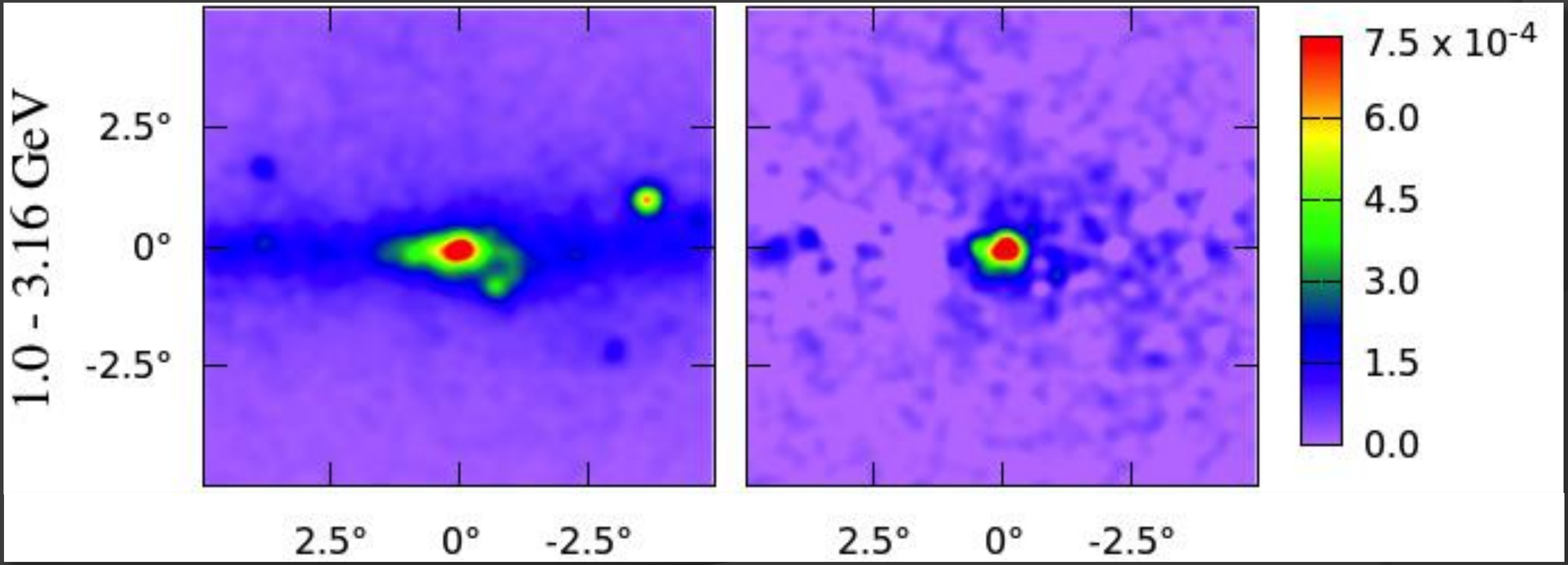
Point 1: Overwhelming Statistical Significance and Detailed Information

(we know a lot about the excess)

- This excess consists of ~10^4 photons per square meter, per year (>1 GeV, within 10° of the Galactic Center)

Raw Map

Residual Map (x3)



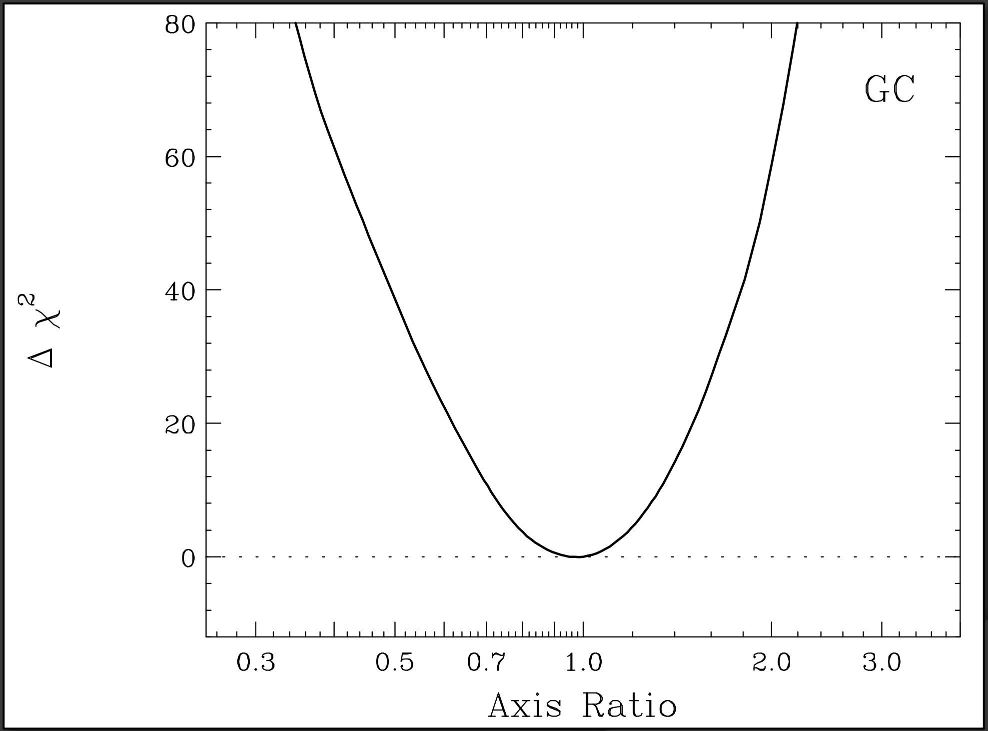
Point 1: Overwhelming Statistical Significance and Detailed Information

(we know a lot about the excess)

- This excess consists of ~10^4 photons per square meter, per year (>1 GeV, within 10° of the Galactic Center)
- In our Inner Galaxy analysis, the quality of the best-fit found with a dark matter component improves over the best-fit without a dark matter component by over 40σ (the Galactic Center analysis "only" prefers a dark matter component at the level of 17σ)

The Detailed Morphology of the Excess

- When we replace the spherically symmetric template (motivated by dark matter) with an elongated template, the fit uniformly worsens
- The axis-ratio of the excess is strongly preferred to be within ~20% of unity



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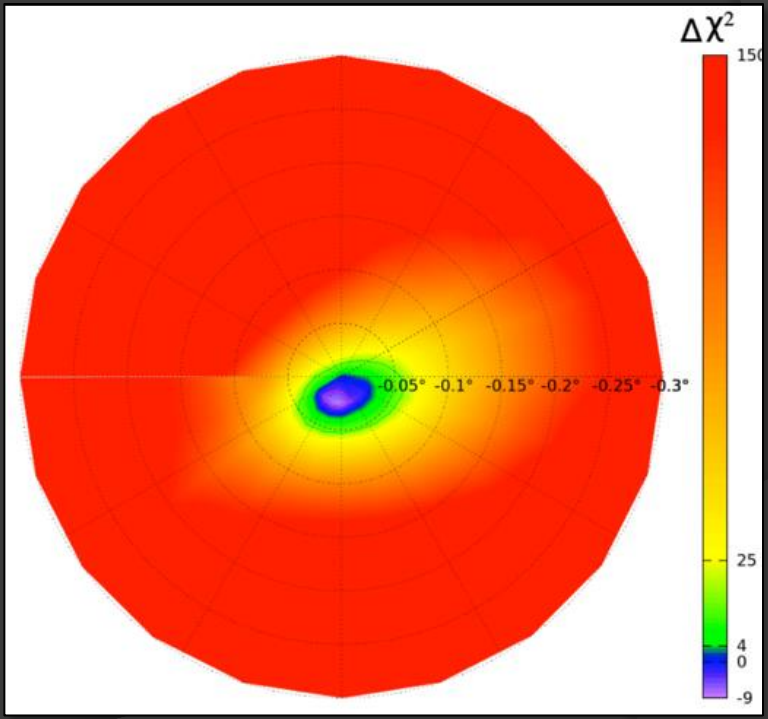
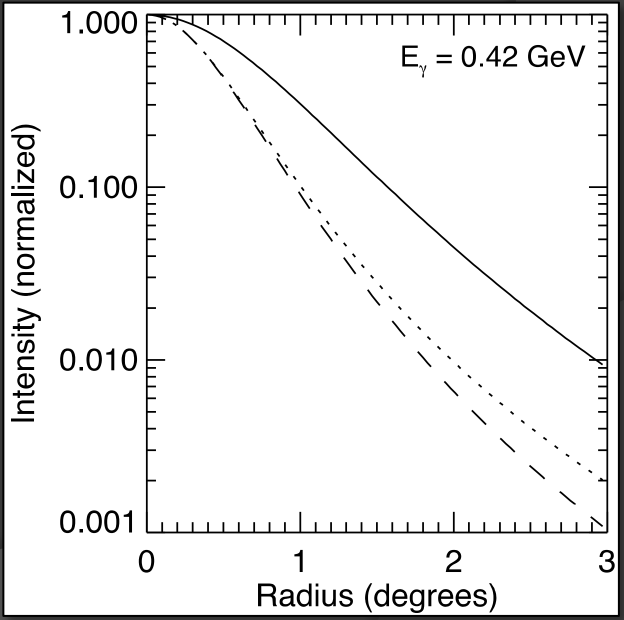
- The axis-ratio of the excess is strongly preferred to be within ~20% of unity
- The excess is also very precisely centered around the dynamical center of the Milky Way, within ~0.03° (~5 pc) of Sgr A*



A Robust Determination of the Signal's Spectrum

- In past studies of this signal (including my own), it was difficult to control systematic uncertainties at low energies (<1 GeV), where Fermi's point spread function (PSF) is large, allowing astrophysical backgrounds from the Galactic Plane and bright point sources to bleed into other regions of interest
- We largely avoid this problem in our analysis by cutting on the parameter CTBCORE, which strongly suppresses the PSF tails

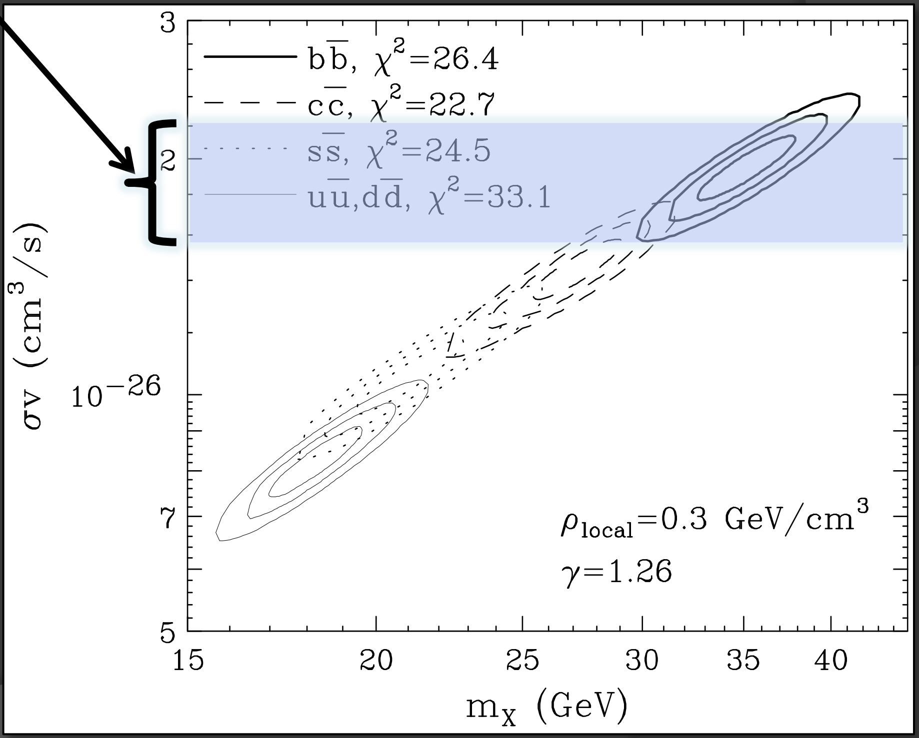


Point 2: It Is Easy To Account For This Signal With Annihilating Dark Matter

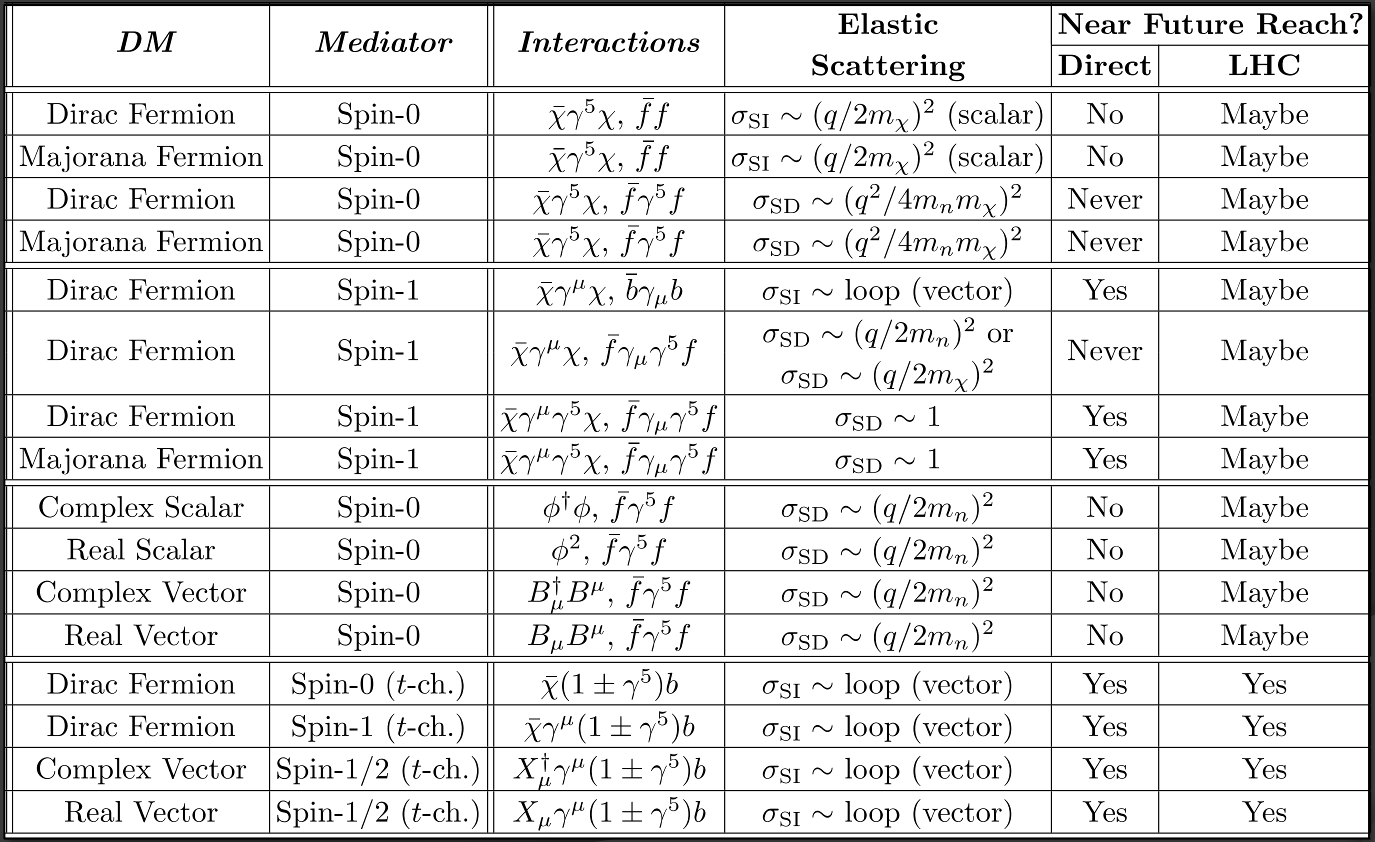
The cross section required to normalize the observed excess is remarkably well-matched to the range of values predicted for a simple (s-wave dominated) thermal relic

Direct detection constraints rule out some models (those with unsuppressed scalar or vector interactions with quarks), but many remain viable

Somewhat contrary to conventional wisdom, the LHC does not yet exclude many of these models



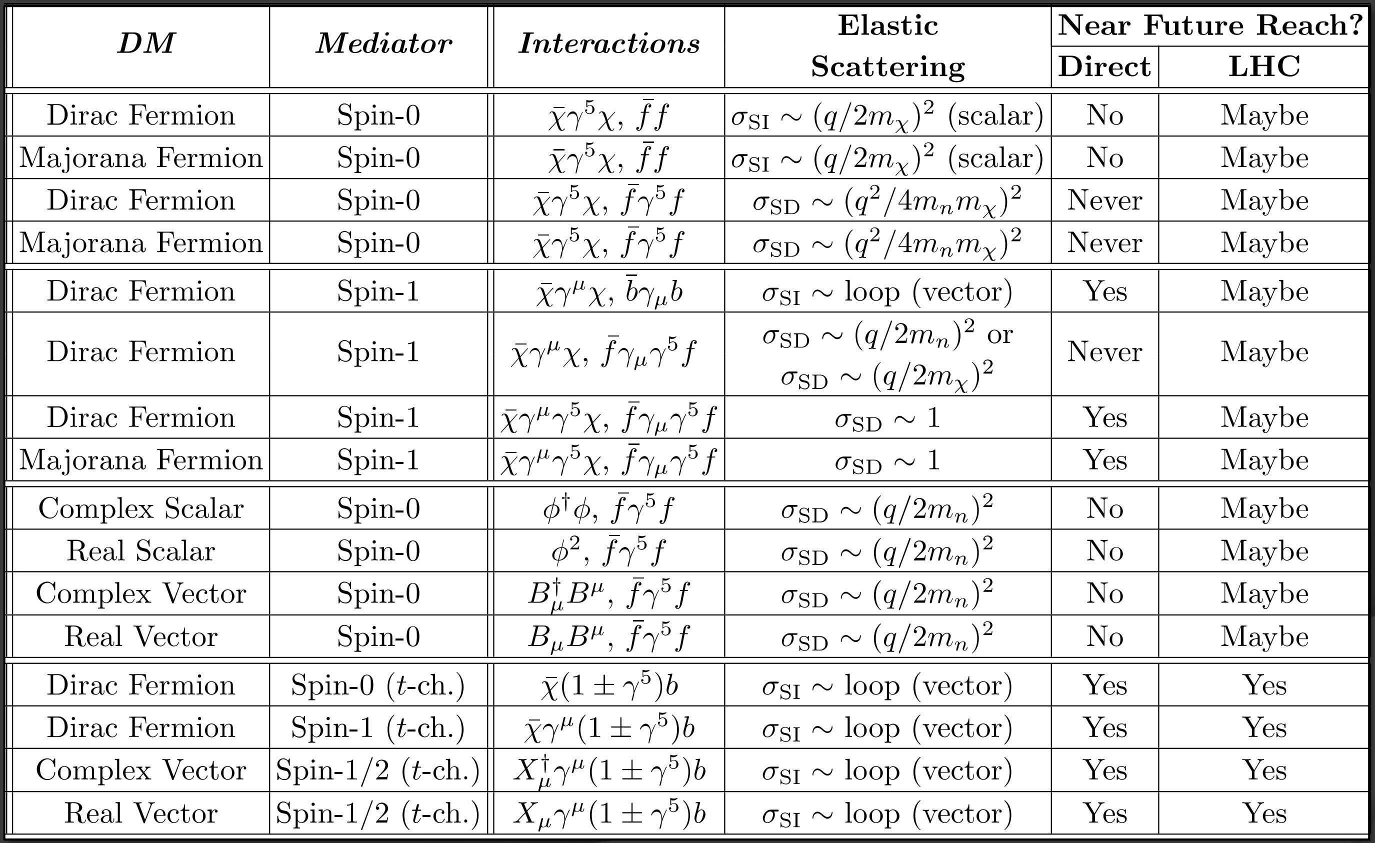
Focusing on dark matter models that annihilate directly to the standard model, we have identified 16 scenarios that could account for the gamma-ray signal without conflicting with current constraints:



DM	***Mediator***	***Interactions***	**Elastic Scattering**	**Near Future Reach?**	
				Direct	**LHC**
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ \bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$ or $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Complex Scalar	Spin-0	$\phi^\dagger\phi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Scalar	Spin-0	$\phi^2,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Complex Vector	Spin-0	$B^\dagger_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Vector	Spin-0	$B_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

Berlin, DH, McDermott,1404.0022

These scenarios roughly fall into three categories:

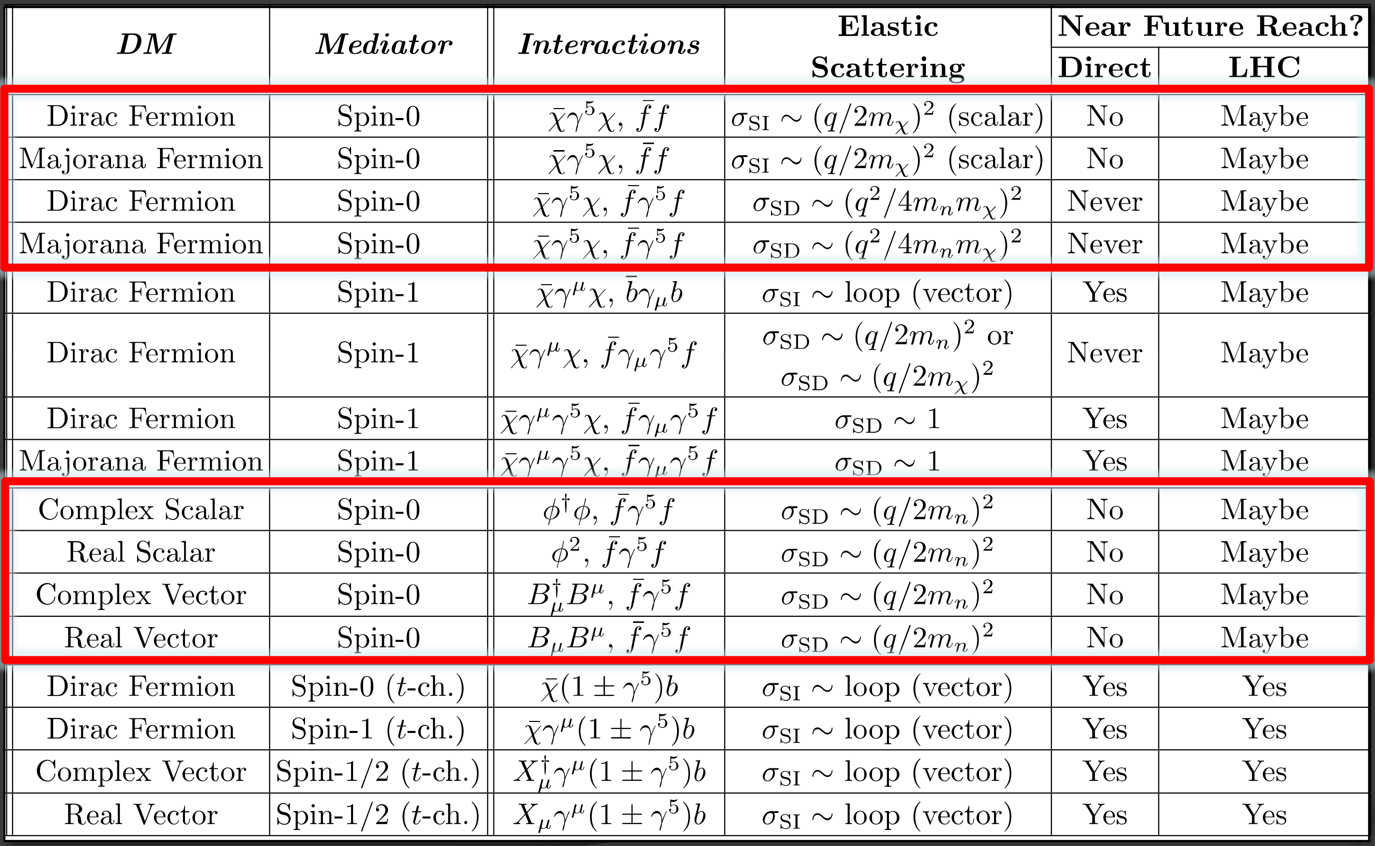


DM	***Mediator***	***Interactions***	**Elastic Scattering**	**Near Future Reach?**	
				Direct	**LHC**
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\mathrm{SI}} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\mathrm{SI}} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ \bar{b}\gamma_\mu b$	$\sigma_{\mathrm{SI}} \sim$ loop (vector)	Yes	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim (q/2m_n)^2$ or $\sigma_{\mathrm{SD}} \sim (q/2m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim 1$	Yes	Maybe
Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim 1$	Yes	Maybe
Complex Scalar	Spin-0	$\phi^\dagger\phi,\ \bar{f}\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim (q/2m_n)^2$	No	Maybe
Real Scalar	Spin-0	$\phi^2,\ \bar{f}\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim (q/2m_n)^2$	No	Maybe
Complex Vector	Spin-0	$B_\mu^\dagger B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim (q/2m_n)^2$	No	Maybe
Real Vector	Spin-0	$B_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim (q/2m_n)^2$	No	Maybe
Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\mathrm{SI}} \sim$ loop (vector)	Yes	Yes
Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\mathrm{SI}} \sim$ loop (vector)	Yes	Yes
Complex Vector	Spin-1/2 (t-ch.)	$X_\mu^\dagger\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\mathrm{SI}} \sim$ loop (vector)	Yes	Yes
Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\mathrm{SI}} \sim$ loop (vector)	Yes	Yes

Berlin, DH, McDermott,1404.0022

These scenarios roughly fall into three categories:

1) Models with pseudoscalar interactions (see also Boehm et al. 1401.6458, Ipek et al. 1404.3716)



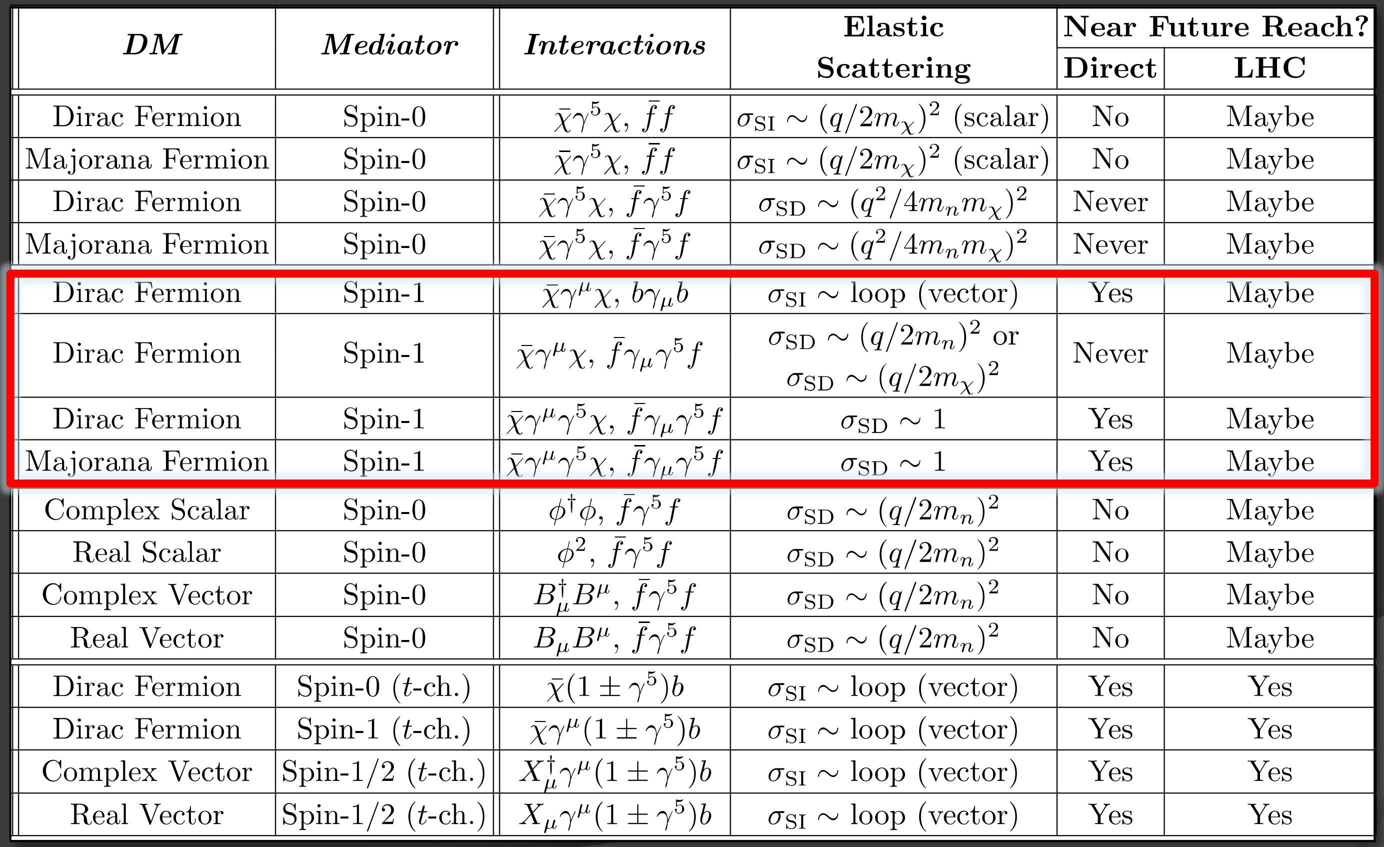
DM	***Mediator***	***Interactions***	**Elastic Scattering**	**Near Future Reach?**	
				Direct	**LHC**
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$ or $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Complex Scalar	Spin-0	$\phi^\dagger\phi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Scalar	Spin-0	ϕ^2, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Complex Vector	Spin-0	$B^\dagger_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Vector	Spin-0	$B_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

Berlin, DH, McDermott,1404.0022

These scenarios roughly fall into three categories:

1) Models with pseudoscalar interactions

2) Models with axial interactions (or vector interactions with 3rd generation)



DM	*Mediator*	*Interactions*	**Elastic Scattering**	**Near Future Reach?**	
				Direct	**LHC**
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\mathrm{SI}} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\mathrm{SI}} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ b\gamma_\mu b$	$\sigma_{\mathrm{SI}} \sim$ loop (vector)	Yes	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim (q/2m_n)^2$ or $\sigma_{\mathrm{SD}} \sim (q/2m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim 1$	Yes	Maybe
Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim 1$	Yes	Maybe
Complex Scalar	Spin-0	$\phi^\dagger\phi,\ \bar{f}\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim (q/2m_n)^2$	No	Maybe
Real Scalar	Spin-0	$\phi^2,\ \bar{f}\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim (q/2m_n)^2$	No	Maybe
Complex Vector	Spin-0	$B^\dagger_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim (q/2m_n)^2$	No	Maybe
Real Vector	Spin-0	$B_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\mathrm{SD}} \sim (q/2m_n)^2$	No	Maybe
Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\mathrm{SI}} \sim$ loop (vector)	Yes	Yes
Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\mathrm{SI}} \sim$ loop (vector)	Yes	Yes
Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\mathrm{SI}} \sim$ loop (vector)	Yes	Yes
Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\mathrm{SI}} \sim$ loop (vector)	Yes	Yes

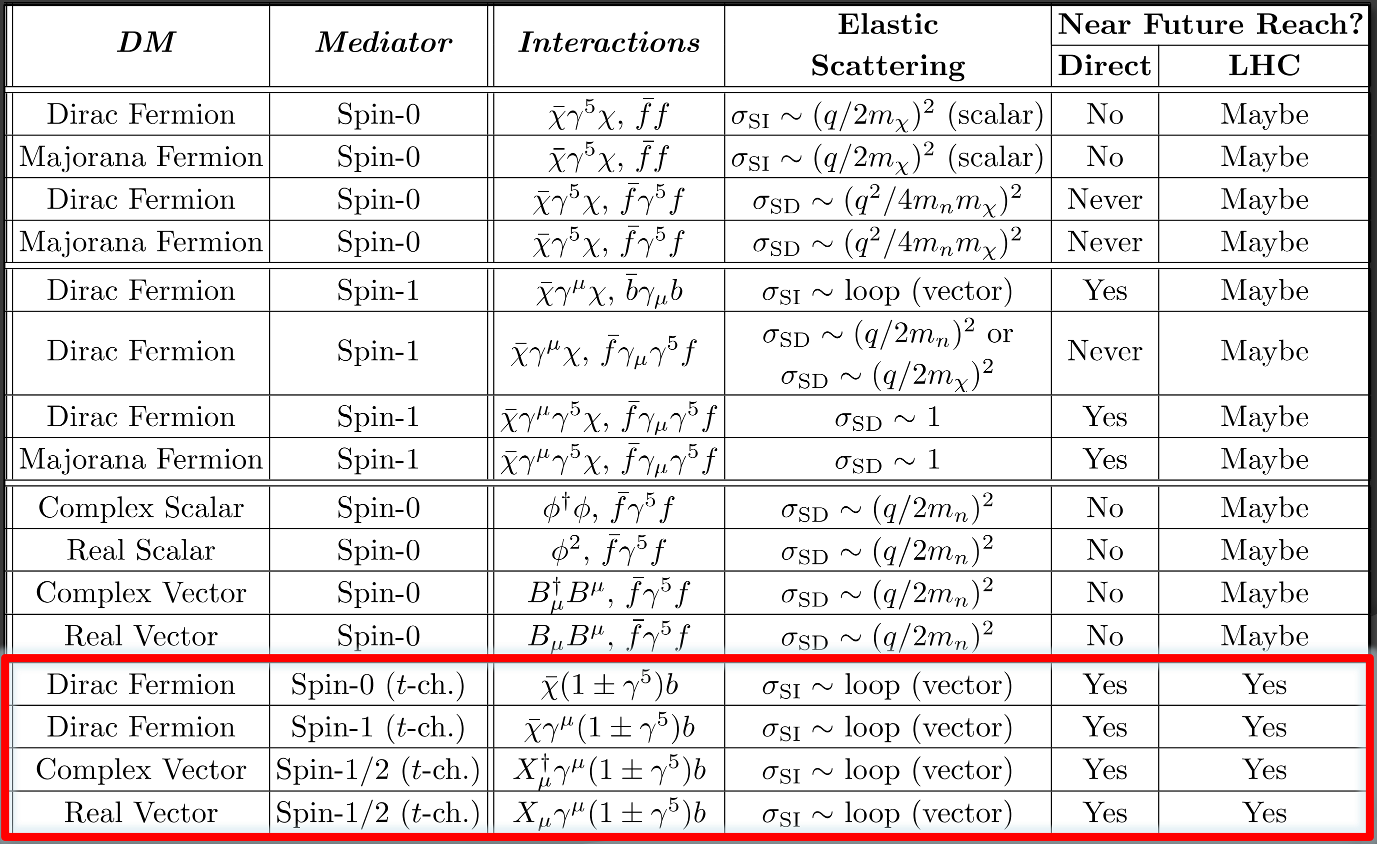
Berlin, DH, McDermott,1404.0022

These scenarios roughly fall into three categories:

1) Models with pseudoscalar interactions

2) Models with axial interactions (or vector interactions with 3rd generation)

3) Models with a colored and charged t-channel mediator (see Agrawal et al. 1404.1373)



DM	***Mediator***	***Interactions***	**Elastic Scattering**	**Near Future Reach?**	
				Direct	**LHC**
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ \bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$ or $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi,\ \bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
Complex Scalar	Spin-0	$\phi^\dagger\phi,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Scalar	Spin-0	$\phi^2,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Complex Vector	Spin-0	$B^\dagger_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Real Vector	Spin-0	$B_\mu B^\mu,\ \bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

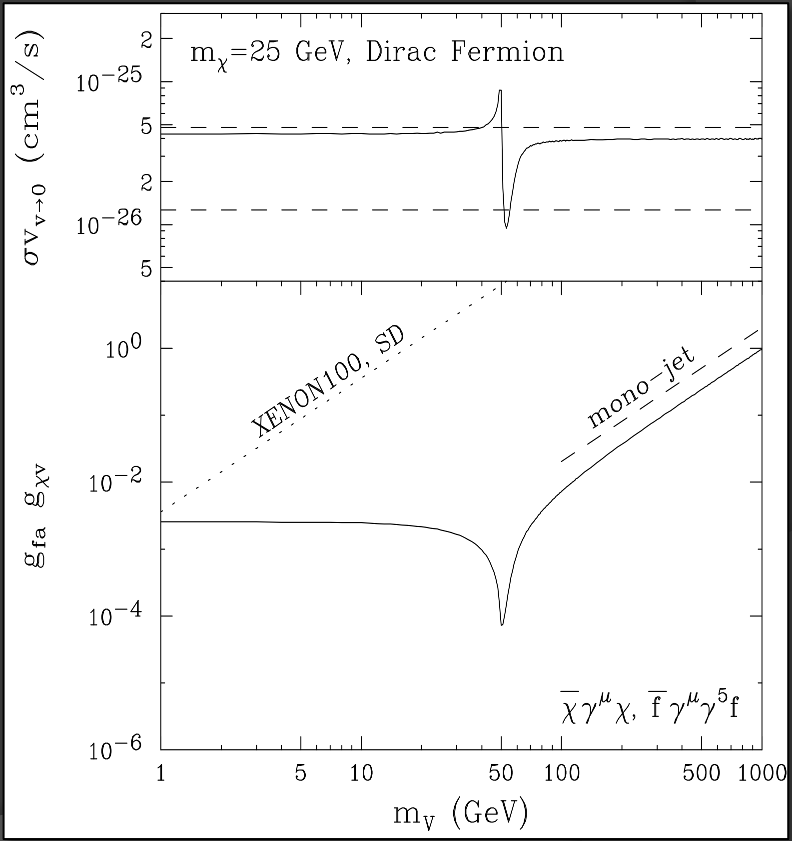
Berlin, DH, McDermott,1404.0022

Constraints from Mono-X

We have also considered constraints (and projected constraints) from mono-jet, mono-b, and mono-W/Z searches at the LHC

-Such searches constrain the coefficients of effective operators, roughly corresponding to $(g_f\ g_X)^{1/2}/M_{med}$

-Reality, however, is only imperfectly described by effective operators



A. Berlin, S. McDermott, DH, 1404.0022

Sidebar: The Validity of Effective Field Theory

When one derives a constraint on the coefficient of an effective operator, they are implicitly assuming that all of the particles being exchanged are much heavier than the center-of-mass energy of the interaction

This assumption can either overestimate or underestimate the actual constraint on the mediator mass and couplings:

M_{med} >> E_{CM}, the correct limit is obtained

M_{med} ~ E_{CM}, the limit is *underestimated*

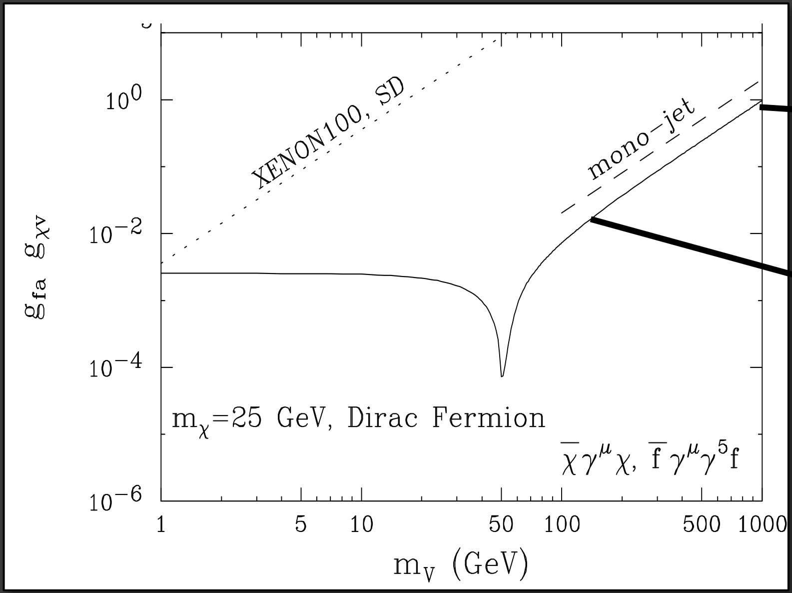
M_{med} << E_{CM}, the limit is *overestimated*

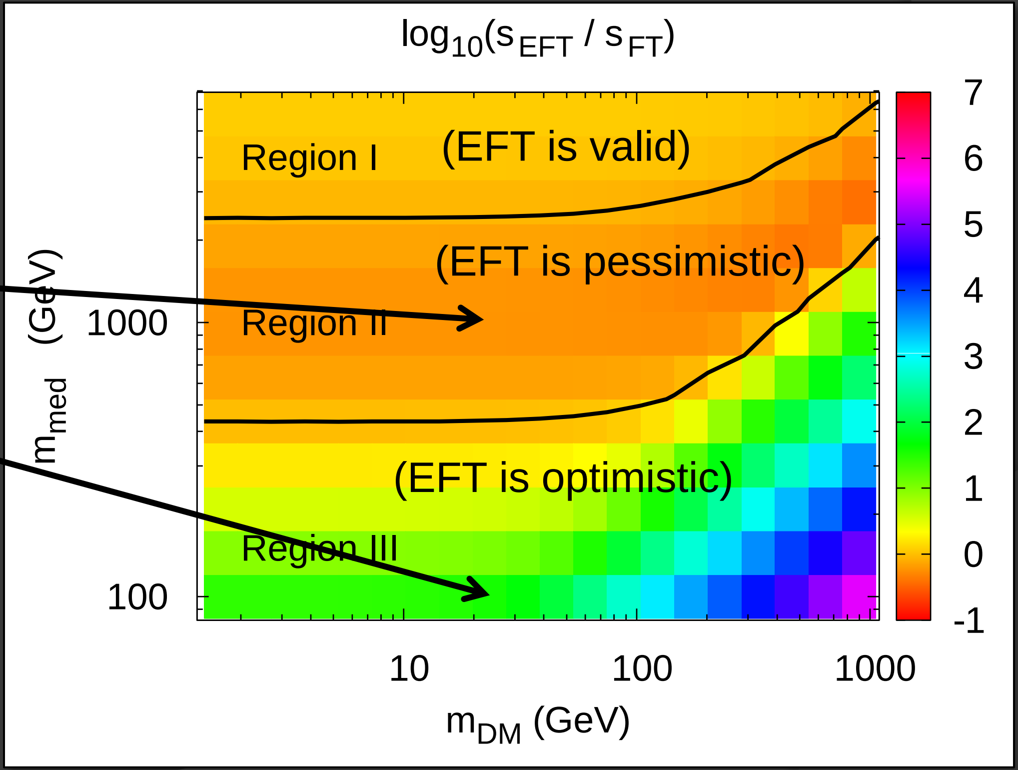
Buckmueller, Dolan, McCabe, 1308.6799

Sidebar: The Validity of Effective Field Theory

For LHC 8 TeV, typical dark matter models do not lie in the “Region I” where EFT is valid

This provides strong motivation to move beyond EFT and toward simplified models





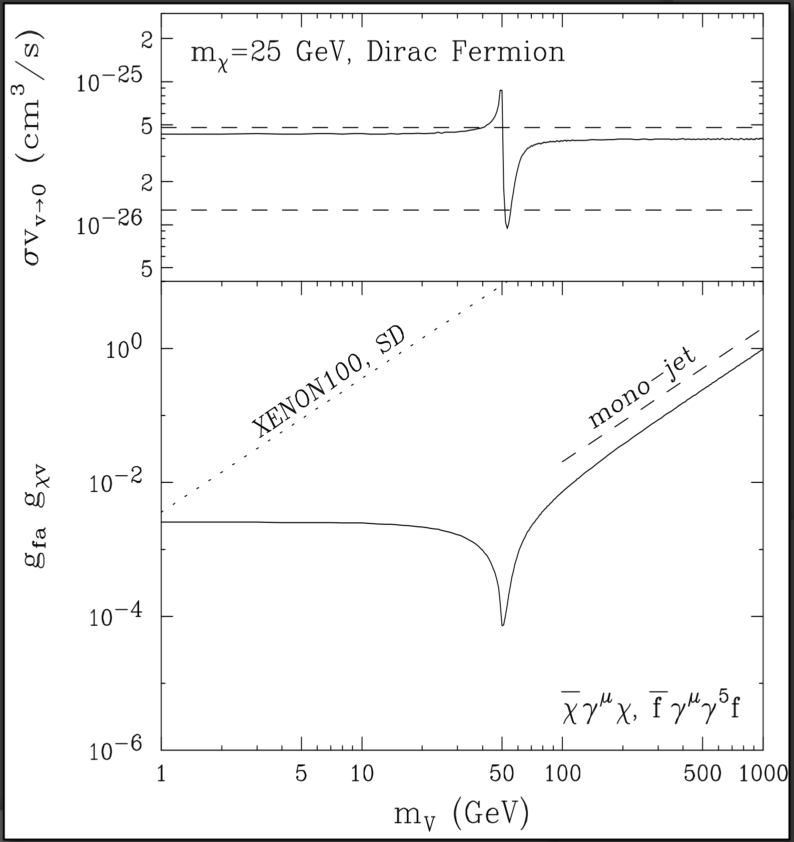
Buckmueller, Dolan, McCabe, 1308.6799

Constraints from Mono-X

In general, we found that current LHC mono-jet constraints are within a factor of a few of that required to test dark matter models for the Galactic Center gamma-ray excess, so long as:

1) The mediating particles couple to light quarks (if couple only to heavy quarks, mono-b constraints are more important)
Data at 13-14 TeV should be able to reach this target!

2) The mass of the mediator is not less than a few hundred GeV
(where EFT breaks down)

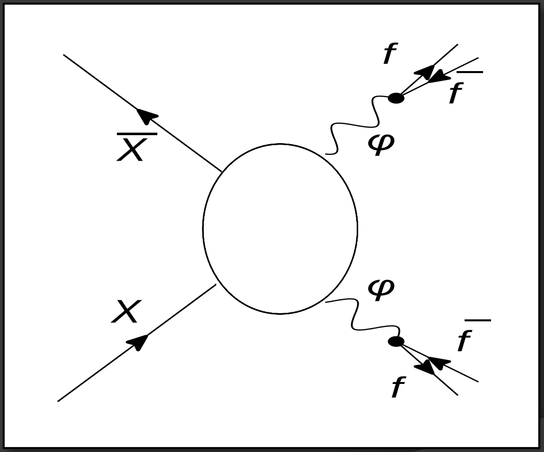


A. Berlin, S. McDermott, DH, 1404.0022

Hidden Sector Models

Although the lack of signals observed in direct detection experiments and at colliders restricts the nature of the dark matter's interactions with the Standard Model, many tree-level annihilation processes continue to be viable

Alternatively, one could take this as motivation to consider dark matter that does not couple directly to the Standard Model, but instead annihilates into other particles that subsequently decay into Standard Model fermions:

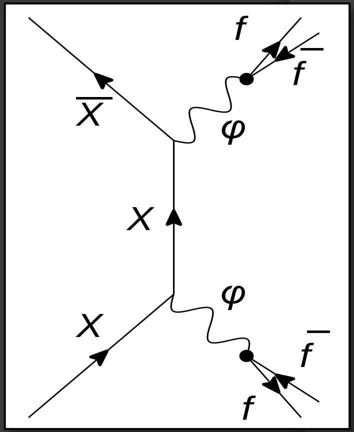


Martin et al. 1405.0272,
Abdullah et al. 1404.6528,
Boehm et al. 1404.4977

Dark Matter with a Hidden Photon

Consider dark matter as a Dirac fermion, with no Standard Model gauge charges, but that is charged under a new U(1)

If the dark matter (X) is more massive than the U(1)'s gauge boson (ϕ), annihilations can proceed through the following:



Relic abundance and Galactic Center annihilation rate require $g_X \sim 0.1$

A. Berlin, S. McDermott, DH, 1405.5204

Dark Matter with a Hidden Photon

Consider dark matter as a Dirac fermion, with no Standard Model gauge charges, but that is charged under a new U(1)

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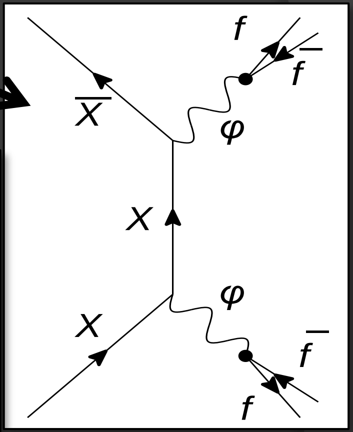
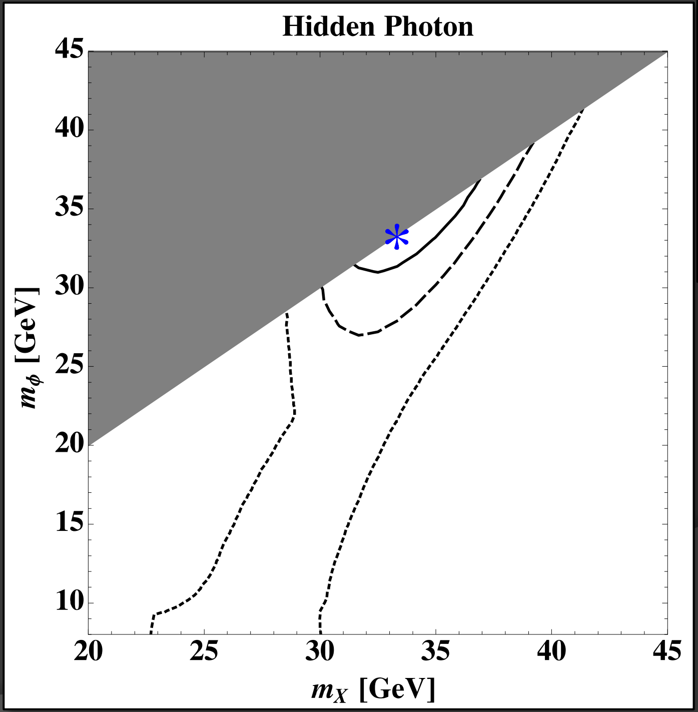


Relic abundance and Galactic Center annihilation rate require $g_X \sim 0.1$

The ϕ's decay through a small degree of kinetic mixing with the photon; direct constraints require mixing less than $\varepsilon \sim 10^{-4}$ (near loop-level prediction)

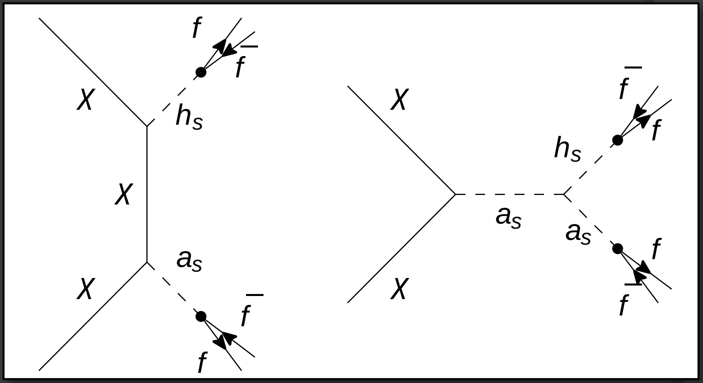


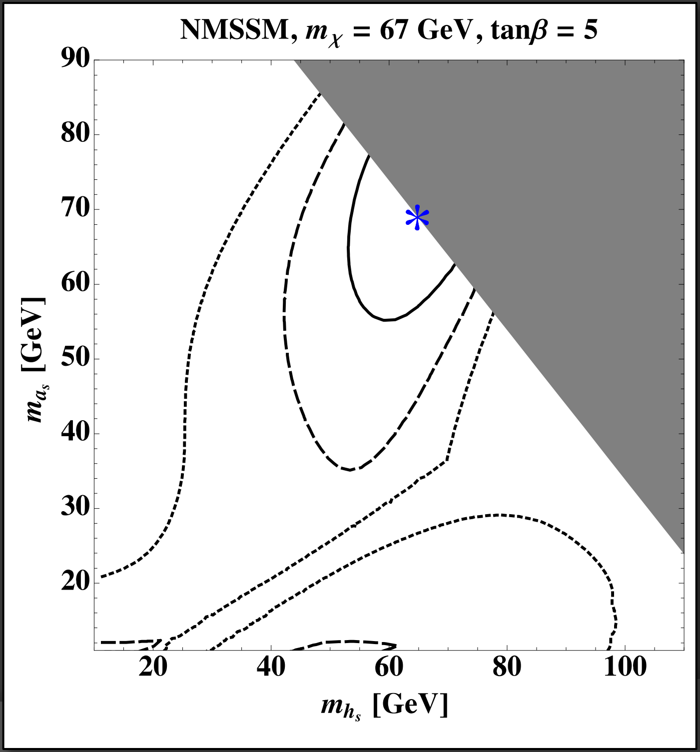
A. Berlin, S. McDermott, DH, 1405.5204

A Supersymmetric Model

Within the context of the generalized NMSSM, the singlino and the complex higgs singlet can be effectively sequestered from the MSSM, allowing for phenomenology similar to in the hidden photon case

Relic abundance and Galactic Center annihilation rate require κ ~ 0.1





The h_s, a_s decay through mass mixing with the MSSM h, A

Direct direct constraints require λ ~ 10^{-3} or less

A. Berlin, S. McDermott, DH, 1405.5204

Point 3: The Lack of a Plausible Alternative Interpretation

This signal does not correlate with the distribution of gas, dust, magnetic fields, cosmic rays, star formation, or radiation

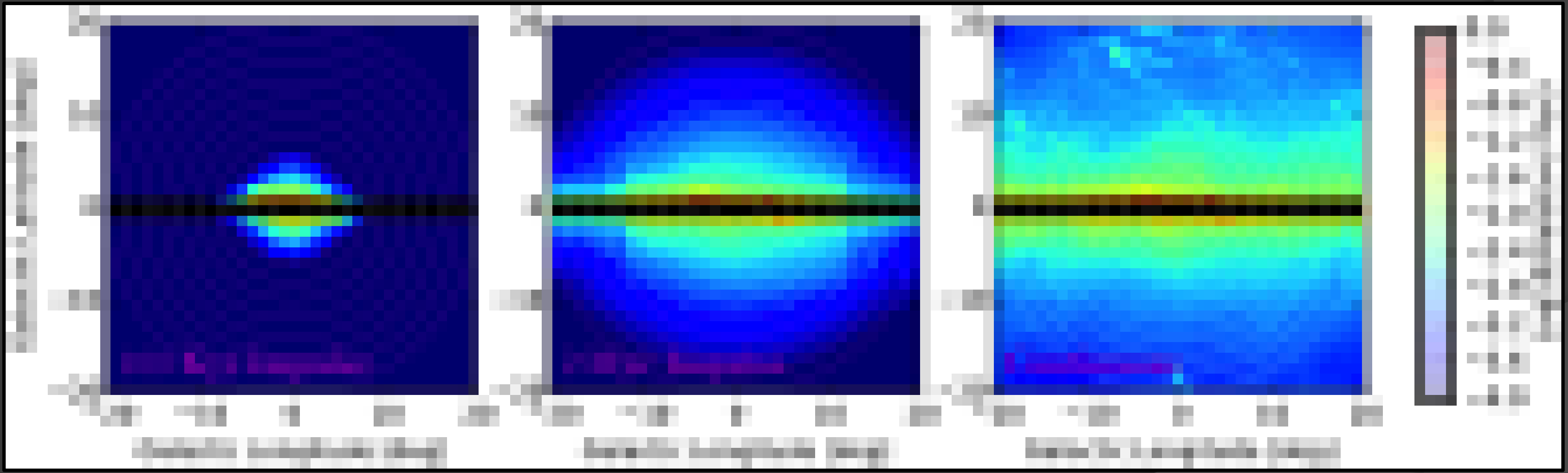
(It does, however, trace quite well the square of the dark matter density, for a profile slightly steeper than NFW)

No known diffuse emission mechanisms can account for this excess

Point 3: The Lack of a Plausible Alternative Interpretation

- Recently, two studies have been presented which propose that a burst-like injection of cosmic rays (~10^6 yrs) might be responsible for the excess

- Carlson and Profumo's hadronic scenario (arXiv:1405.7685) predicts a gamma-ray signal with the following morphology:



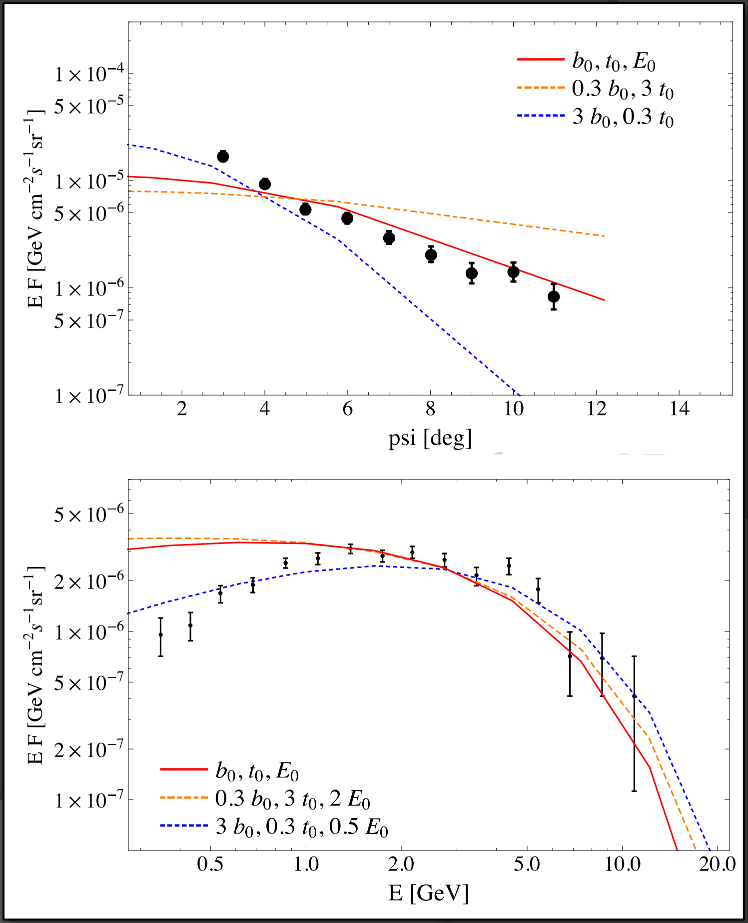
- Our Galactic Center fit strongly prefers a much more spherical distribution – these morphologies can be strongly ruled out by the data

Point 3: The Lack of a Plausible Alternative Interpretation

Recently, two studies have been presented which propose that a burst-like injection of cosmic rays (~10^6 yrs) might be responsible for the excess

A leptonic scenario might be able to yield a more spherical morphology, but struggles to simultaneously fit both the spectrum and angular profile of the excess

Furthermore, our fits include a 20 cm (synchrotron) template, which does not correlate with the excess – if it originates electrons, it would be expected to



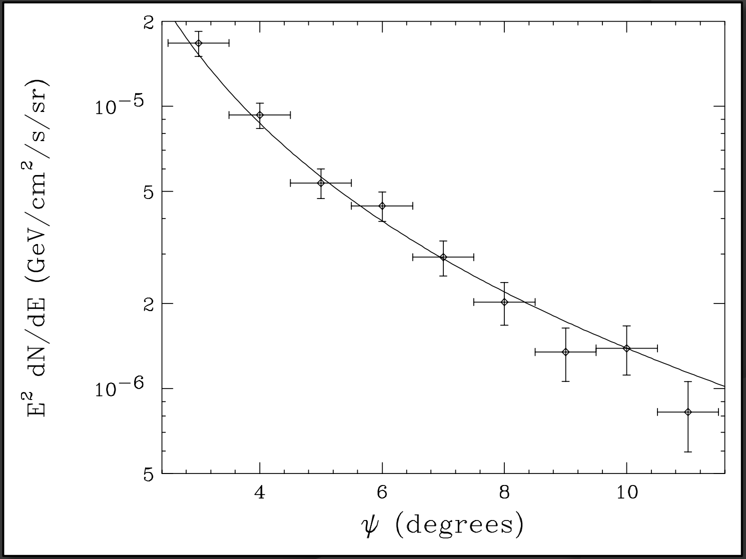
(Petrovic, Serpico, Zaharijas, arXiv:1405.7928)

Point 3: The Lack of a Plausible Alternative Interpretation

The most often discussed astrophysical interpretation for this signal is a population of several thousand millisecond pulsars (MSPs) associated with the Milky Way's central stellar cluster – such a population could plausibly account for much of the excess observed within the innermost ~1-2° of the Galaxy

But we observe this excess to extend out to at least ~10° from the Galactic Center

If MSPs were distributed in a way that could account for this extended excess, Fermi should have resolved many more as individual point sources than they did



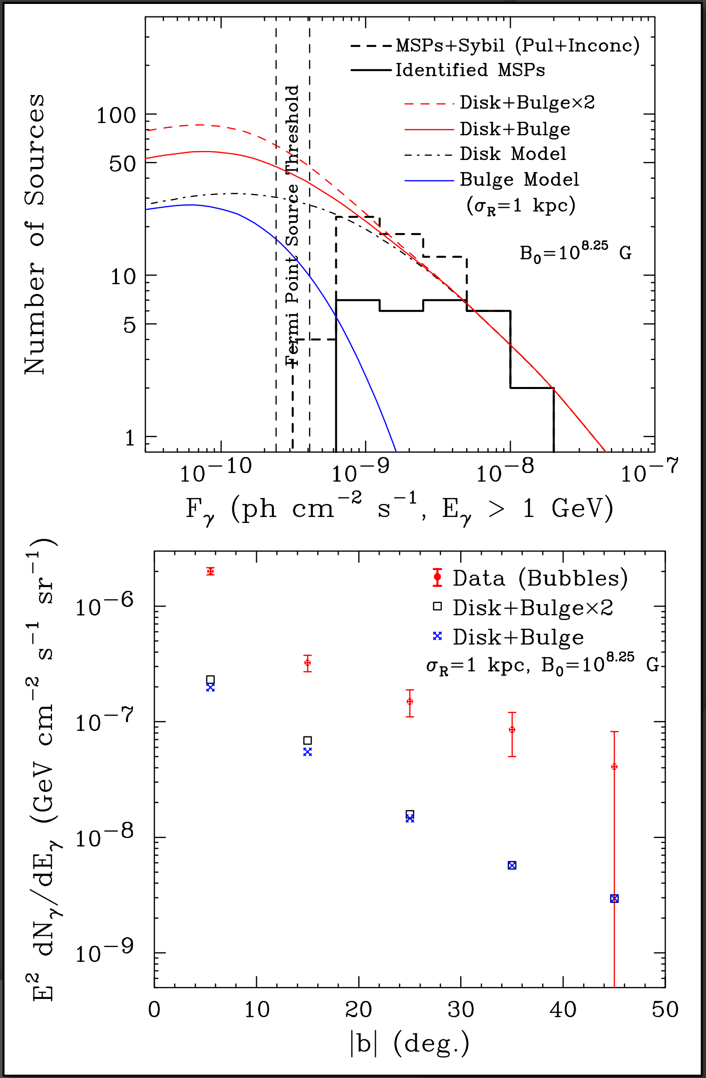
Point 3: The Lack of a Plausible Alternative Interpretation

We find that no more than ~5-10% of the excess beyond ~ 5° can come from MSPs (DH, Cholis, Linden, Siegal-Gaskins, Slatyer, PRD, arXiv:1305.0830; Calore et al. arXiv:1406.2706)

This conclusion was further strengthened by recent measurements of the MSP luminosity function (Cholis, DH, Linden, arXiv:1407.5583, 1407.5625)

To evade this conclusion, the luminosity function of bulge MSPs would have to be very different from the luminosity function of observed MSPs, consistently less bright than ~10^{34} erg/s

A comparison of LMXBs and MSPs in globular clusters leads us to expect that a few percent of the excess might arise from MSPs (Cholis, DH, Linden, arXiv:1407.5625)

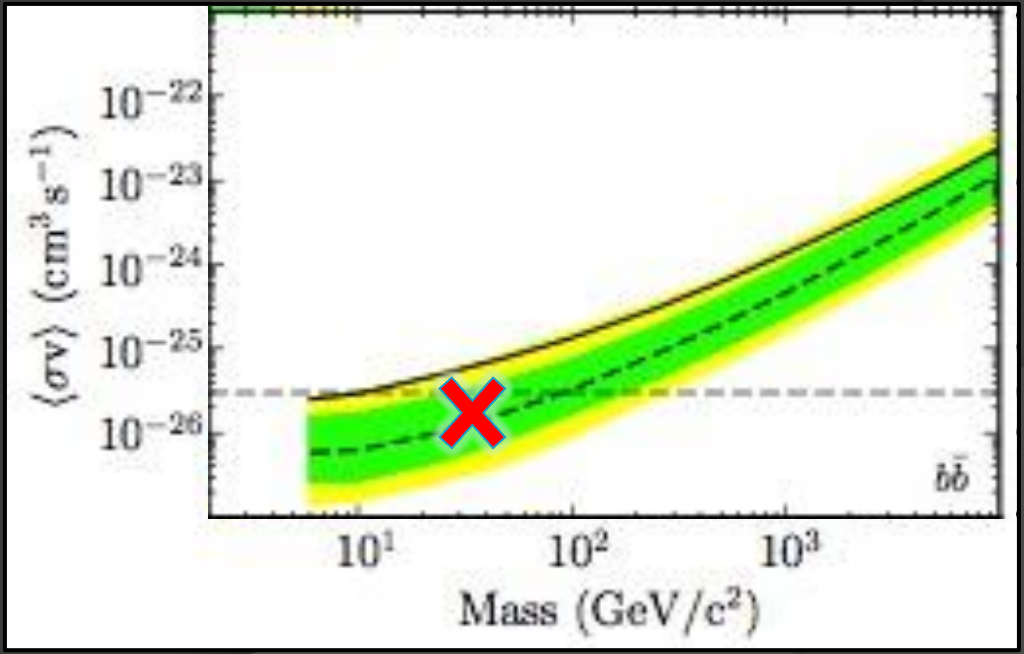


Point 4: A Dark Matter Interpretation of the Galactic Center Excess Provides Testable Predictions

Dwarf Spheroidal Galaxies

- The Fermi Collaboration has recently presented their analysis of 25 dwarf spheroidal galaxies, making use of 4 years of data
- They find a modest excess, ~2-3σ (local)
- If interpreted as a signal of dark matter, this would imply a mass and cross section that is very similar to that required to account for the Galactic Center and Inner Galaxy excess
- With more data from Fermi, this hint could potentially become statistically significant
- For 10 years of data, we very naively estimate: (2-3) σ x $(10/4)^{1/2}$ ➔(3.2-4.7) σ

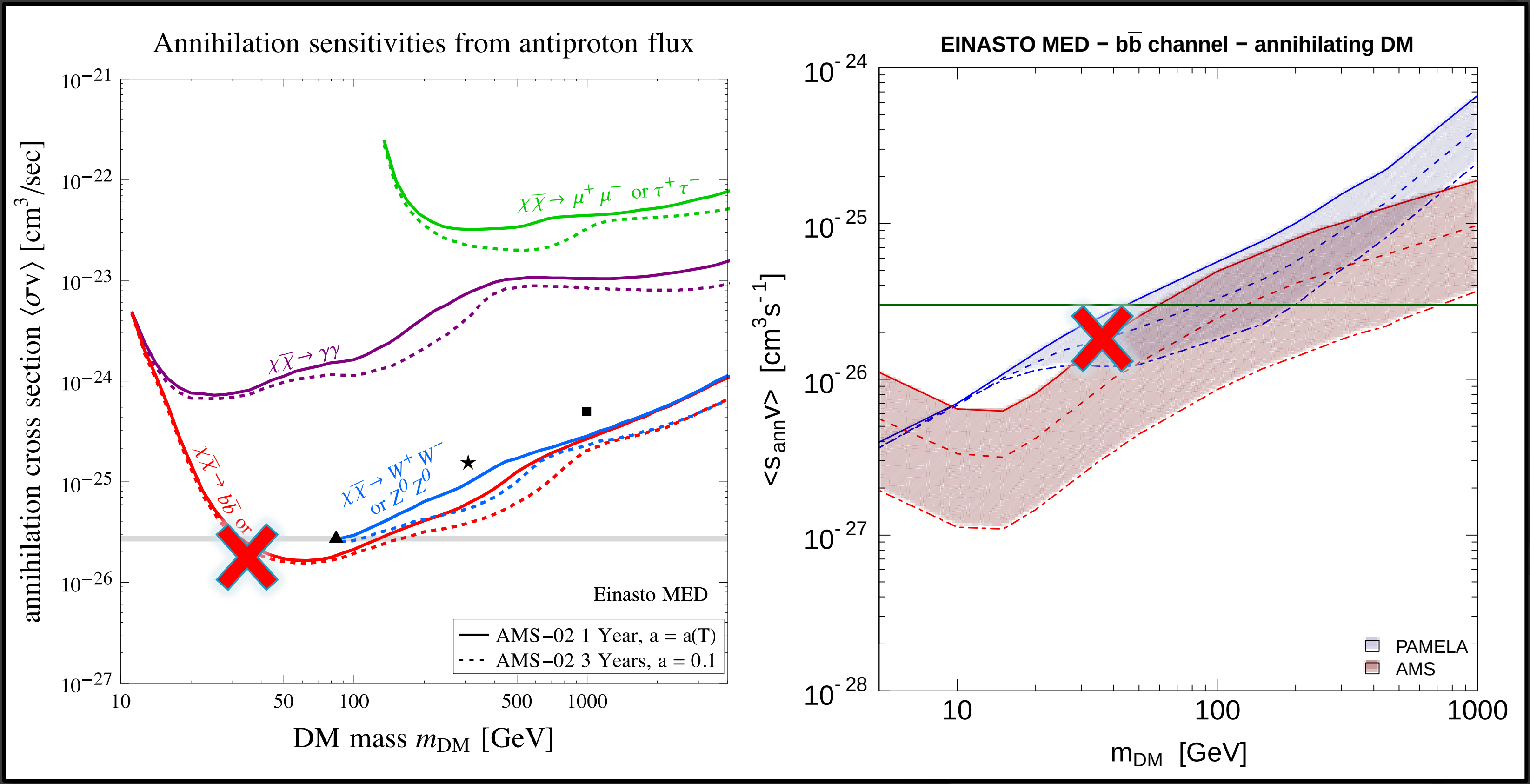
(not including transition to pass 8)



Fermi Collaboration, arXiv:1310.0828

Cosmic Ray Antiprotons

- Although PAMELA wasn’t sensitive enough to test the dark model models in question, AMS might be (depending on the details of diffusion, convection and charge dependent solar modulation)

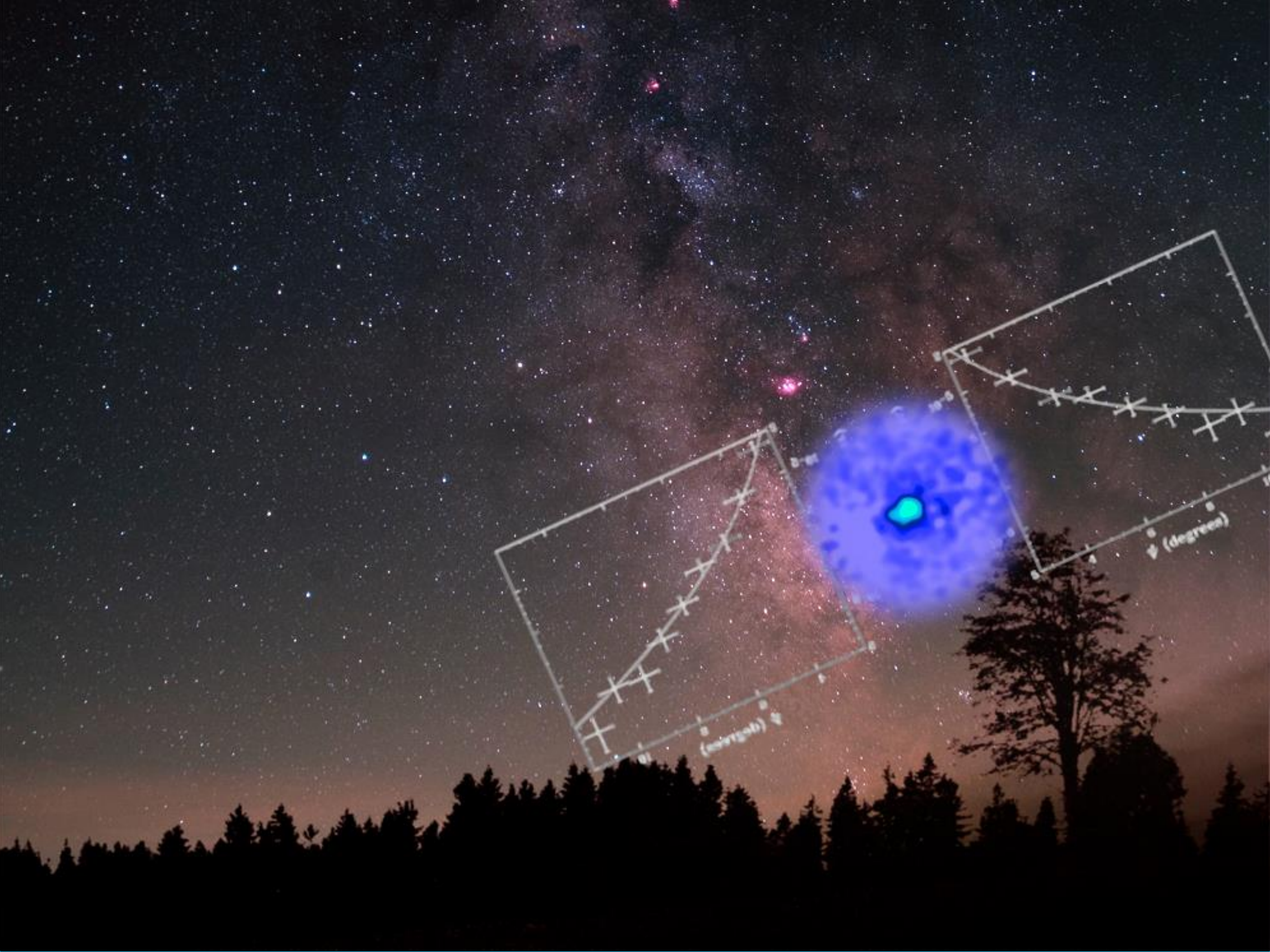


Cirelli, Giesen, 1301.7079 Fornengo et al.1312.3579

(see also Kong and Park, 1404.3741, Cirelli *et al*. 1407.2173)

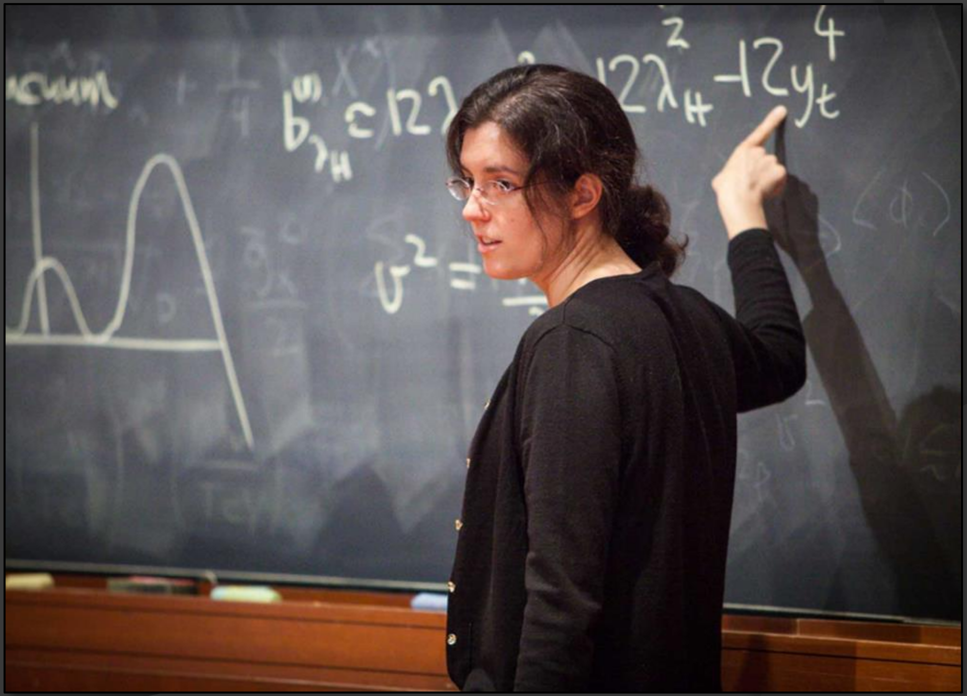
Summary

- Although many indirect detection anomalies have appeared over the years, the Galactic Center's GeV excess is particularly compelling
- The excess is highly statistically significant, robust, and distributed with approximate spherical symmetry, extending out to at least 10° from the Galactic Center – very difficult to explain with known/proposed astrophysics
- The spectrum and angular distribution of this signal is very well fit by a 31-40 GeV WIMP (annihilating to b quarks), distributed as $\rho \sim r^{-1.25}$
- The normalization of this signal requires a dark matter annihilation cross section of $\sigma v \sim (1.7\text{-}2.3) \times 10^{-26}$ cm^3/s (for $\rho_{local} = 0.3$ GeV/cm^3); this is in remarkable agreement with the value predicted for a simple thermal relic
- Many simple dark matter models can account for the observed emission without conflicting with constraints from direct detection experiments or colliders – future prospects are encouraging
- Future observations (dwarfs, cosmic-ray antiprotons, etc.) will be important to confirm a dark matter origin of this signal


ψ (degrees)

Acknowledgement

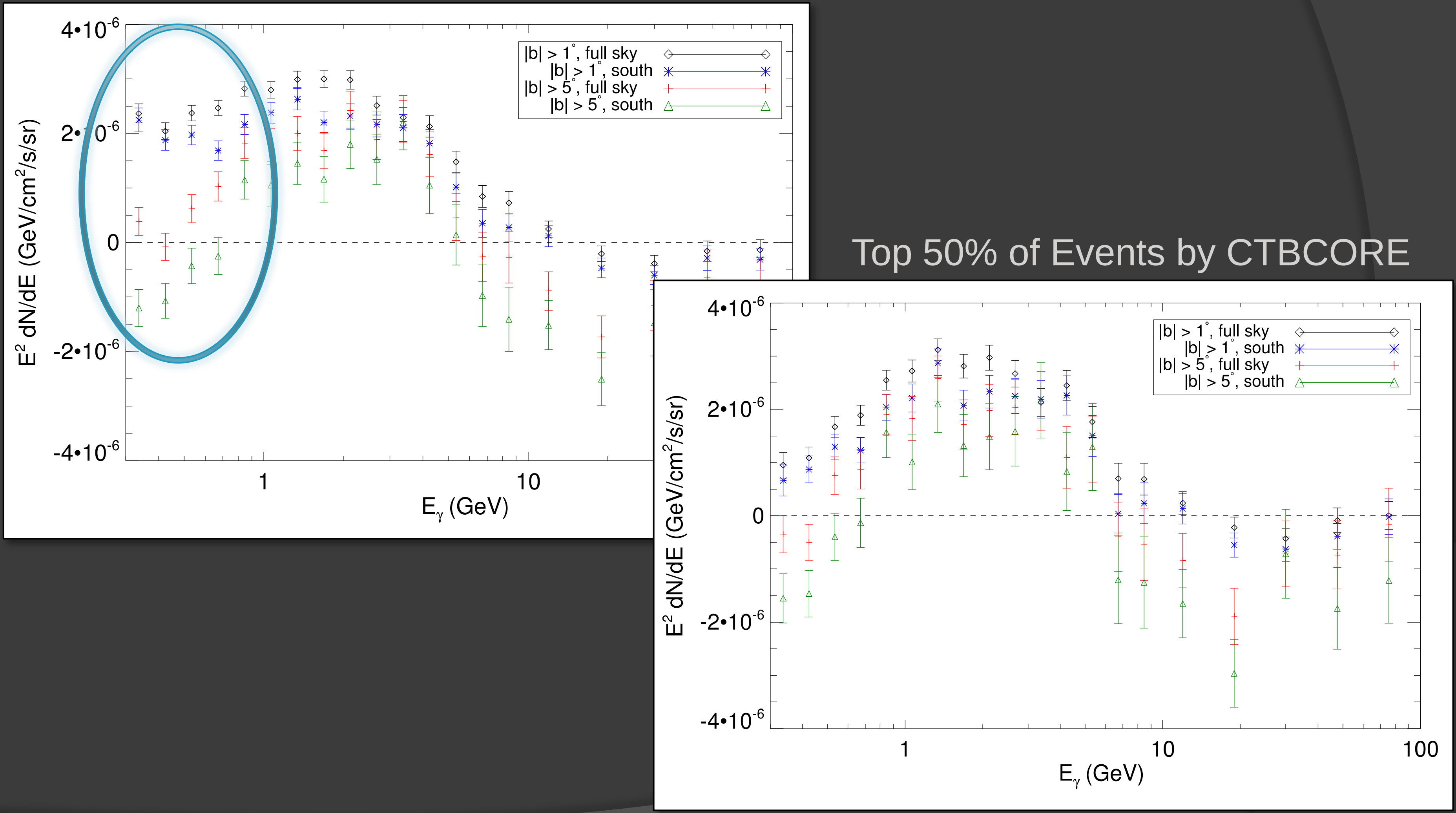
- In 2007, Kathryn Zurek and I made a bet regarding whether dark matter would be definitely discovered by 2012 (I bet that it would be)
- In 2012, the situation was not clear – we agreed to wait and see whether direct detection anomalies persisted to determine the winner (in 2012, the gamma-ray excess was not yet as clear as it is today)
- In light of the null results from SuperCDMS and LUX, I recently conceded our bet
- In the language of the original bet, the loser agreed to acknowledge their loss in every talk they give for an entire year (and thus this slide…)

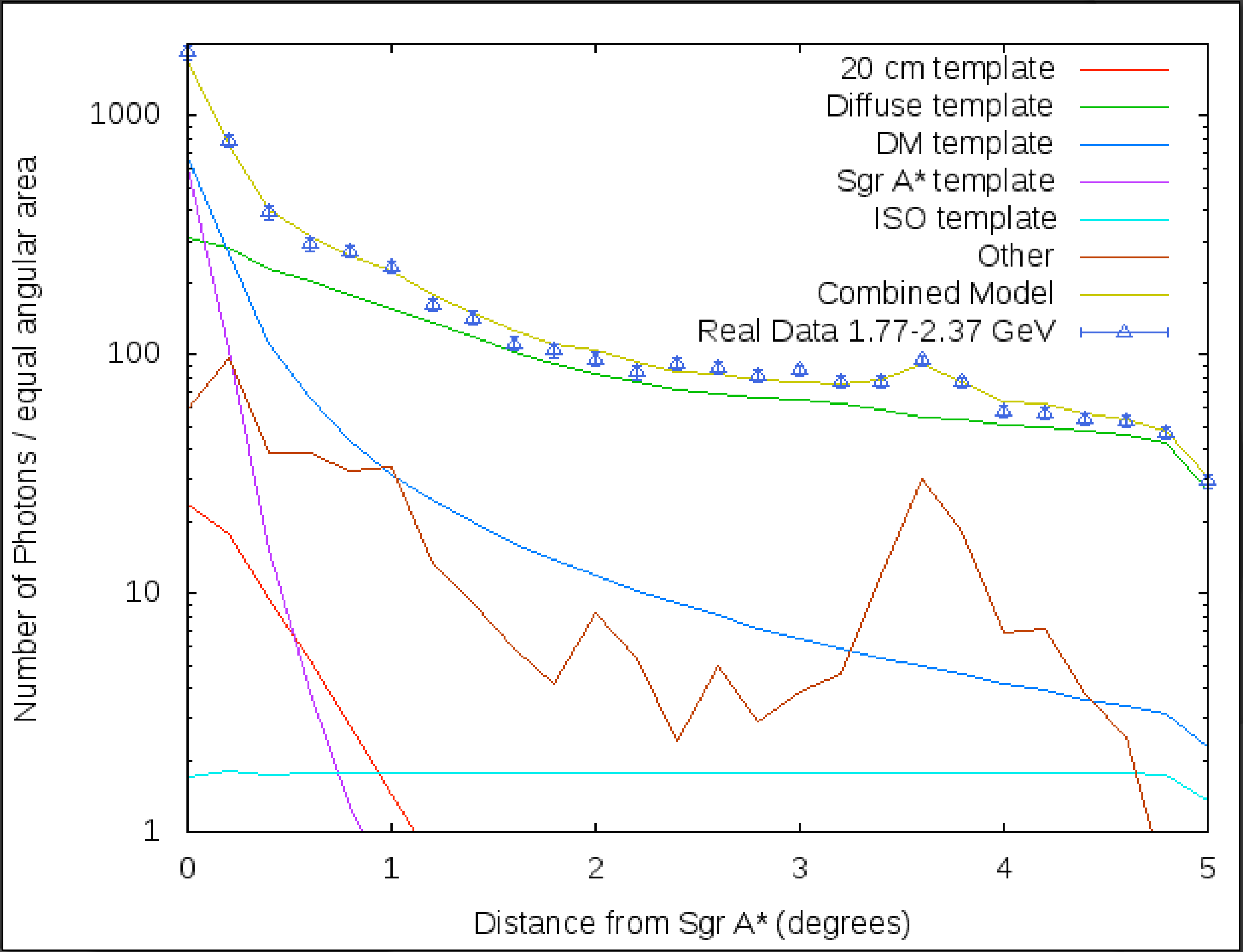


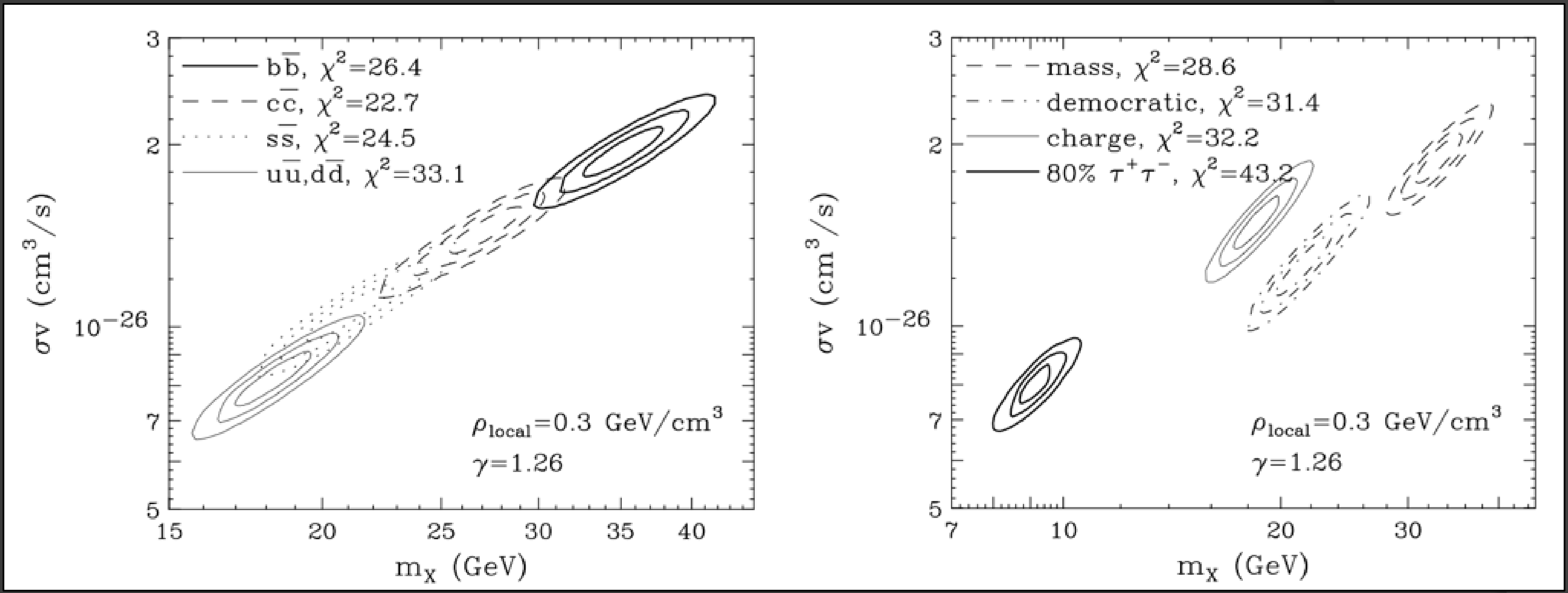
The Utility of Cutting by CTBCORE

Without additional CTBCORE Cuts

Top 50% of Events by CTBCORE




20 cm template
Diffuse template
DM template
Sgr A* template
ISO template
Other
Combined Model
Real Data 1.77-2.37 GeV
Number of Photons / equal angular area
1000
100
10
1
0
1
2
3
4
5
Distance from Sgr A* (degrees)



$b\bar{b}$, χ^2=26.4
$c\bar{c}$, χ^2=22.7
$s\bar{s}$, χ^2=24.5
$u\bar{u}$,$d\bar{d}$, χ^2=33.1
$\rho_{\rm local}$=0.3 GeV/cm^3
γ=1.26
σv (cm^3/s)
m_χ (GeV)
3
2
10^{-26}
7
5
15
20
25
30
35
40
mass, χ^2=28.6
democratic, χ^2=31.4
charge, χ^2=32.2
80% $\tau^+\tau^-$, χ^2=43.2
$\rho_{\rm local}$=0.3 GeV/cm^3
γ=1.26
σv (cm^3/s)
m_χ (GeV)
3
2
10^{-26}
7
5
7
10
20
30

What kind of WIMP could produce this signal?

What kind of WIMP could produce this signal?

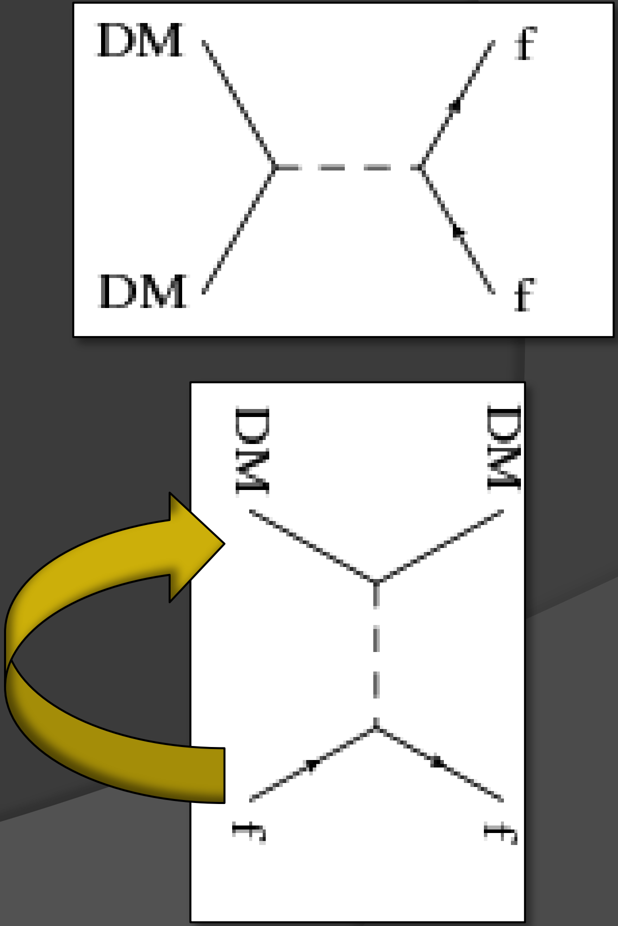
A simple approach:

For a given a tree-level process for dark matter annihilation (specifying the spins and interactions), and fixing the couplings to obtain the desired relic abundance, we ask:

1) Can we get a gamma-ray signal that is compatible the observed excess?

2) Is the related diagram compatible with direct detection constraints?

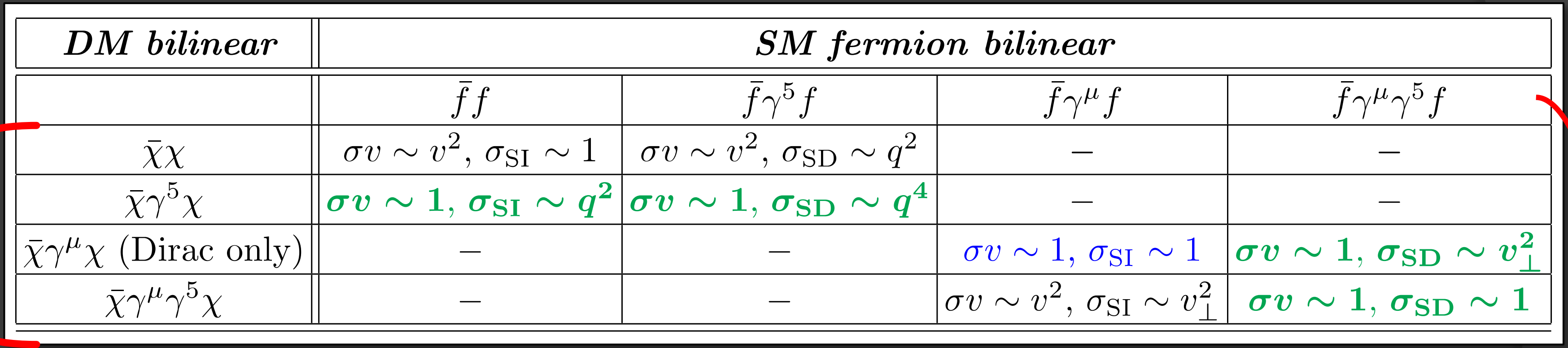
3) Is the model compatible with constraints from colliders (including the LHC)?



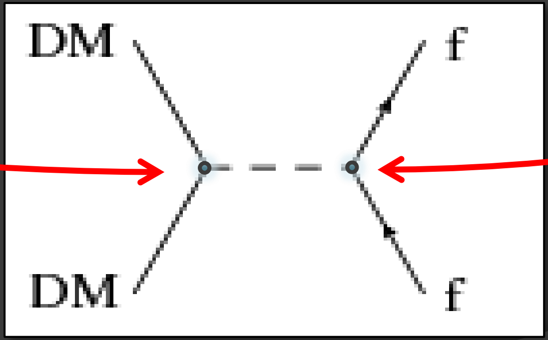
Berlin, DH, McDermott,1404.0022
(see also Alves et al. 1403.5027; Izaguirre et al. 1404.2018)

What kind of WIMP could produce this signal?

For example, consider fermionic dark matter, annihilating through the exchange of a spin-0 or spin-1 mediator:



DM bilinear	***SM fermion bilinear***			
	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\bar{\chi}\chi$	$\sigma v \sim v^2,\ \sigma_{\rm SI} \sim 1$	$\sigma v \sim v^2,\ \sigma_{\rm SD} \sim q^2$	$-$	$-$
$\bar{\chi}\gamma^5\chi$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SI} \sim q^2}$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim q^4}$	$-$	$-$
$\bar{\chi}\gamma^\mu\chi$ (Dirac only)	$-$	$-$	$\sigma v \sim 1,\ \sigma_{\rm SI} \sim 1$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim v_\perp^2}$
$\bar{\chi}\gamma^\mu\gamma^5\chi$	$-$	$-$	$\sigma v \sim v^2,\ \sigma_{\rm SI} \sim v_\perp^2$	$\boldsymbol{\sigma v \sim 1,\ \sigma_{\rm SD} \sim 1}$



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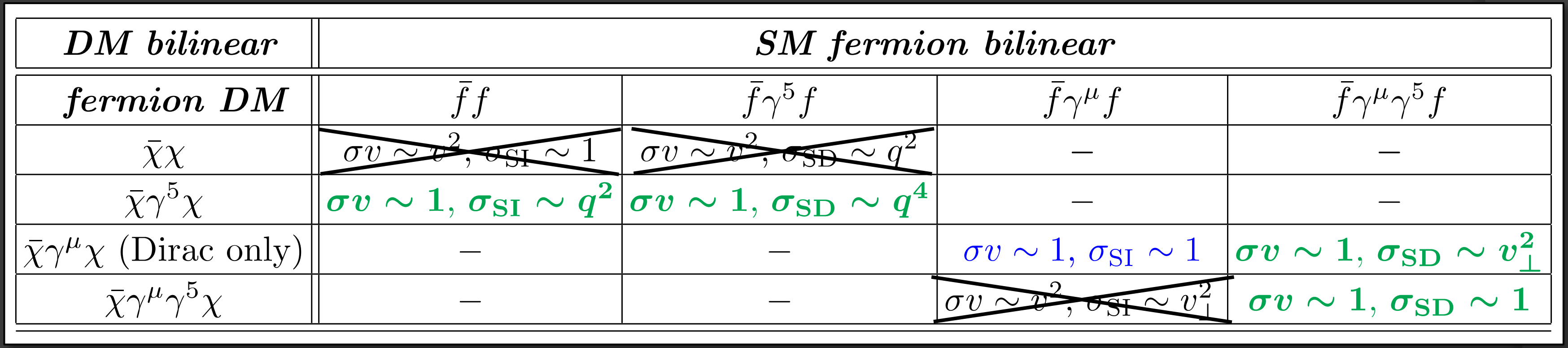

DM bilinear	***SM fermion bilinear***			
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$\bar{\chi}\gamma^\mu\chi$ (Dirac only)	–	–	$\sigma v \sim 1, \sigma_{\rm SI} \sim 1$	$\boldsymbol{\sigma v \sim 1, \sigma_{\rm SD} \sim v_\perp^2}$
$\bar{\chi}\gamma^\mu\gamma^5\chi$	–	–	$\xcancel{\sigma v \sim v^2, \sigma_{\rm SI} \sim v_\perp^2}$	$\boldsymbol{\sigma v \sim 1, \sigma_{\rm SD} \sim 1}$

-Models with velocity suppressed annihilation cross sections cannot account for the gamma-ray excess

Berlin, DH, McDermott,1404.0022

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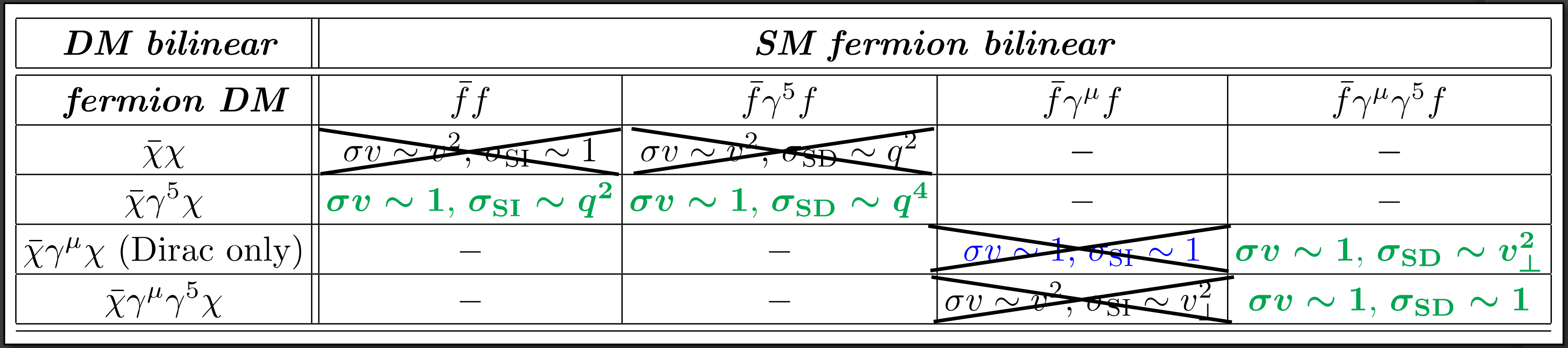


DM bilinear	***SM fermion bilinear***			
fermion DM	$\bar{f}f$	$\bar{f}\gamma^5 f$	$\bar{f}\gamma^\mu f$	$\bar{f}\gamma^\mu\gamma^5 f$
$\bar{\chi}\chi$	~~$\sigma v \sim v^2, \sigma_{\rm SI} \sim 1$~~	~~$\sigma v \sim v^2, \sigma_{\rm SD} \sim q^2$~~	–	–
$\bar{\chi}\gamma^5\chi$	$\boldsymbol{\sigma v \sim 1, \sigma_{\rm SI} \sim q^2}$	$\boldsymbol{\sigma v \sim 1, \sigma_{\rm SD} \sim q^4}$	–	–
$\bar{\chi}\gamma^\mu\chi$ (Dirac only)	–	–	~~$\sigma v \sim 1, \sigma_{\rm SI} \sim 1$~~	$\boldsymbol{\sigma v \sim 1, \sigma_{\rm SD} \sim v_\perp^2}$
$\bar{\chi}\gamma^\mu\gamma^5\chi$	–	–	~~$\sigma v \sim v^2, \sigma_{\rm SI} \sim v_\perp^2$~~	$\boldsymbol{\sigma v \sim 1, \sigma_{\rm SD} \sim 1}$

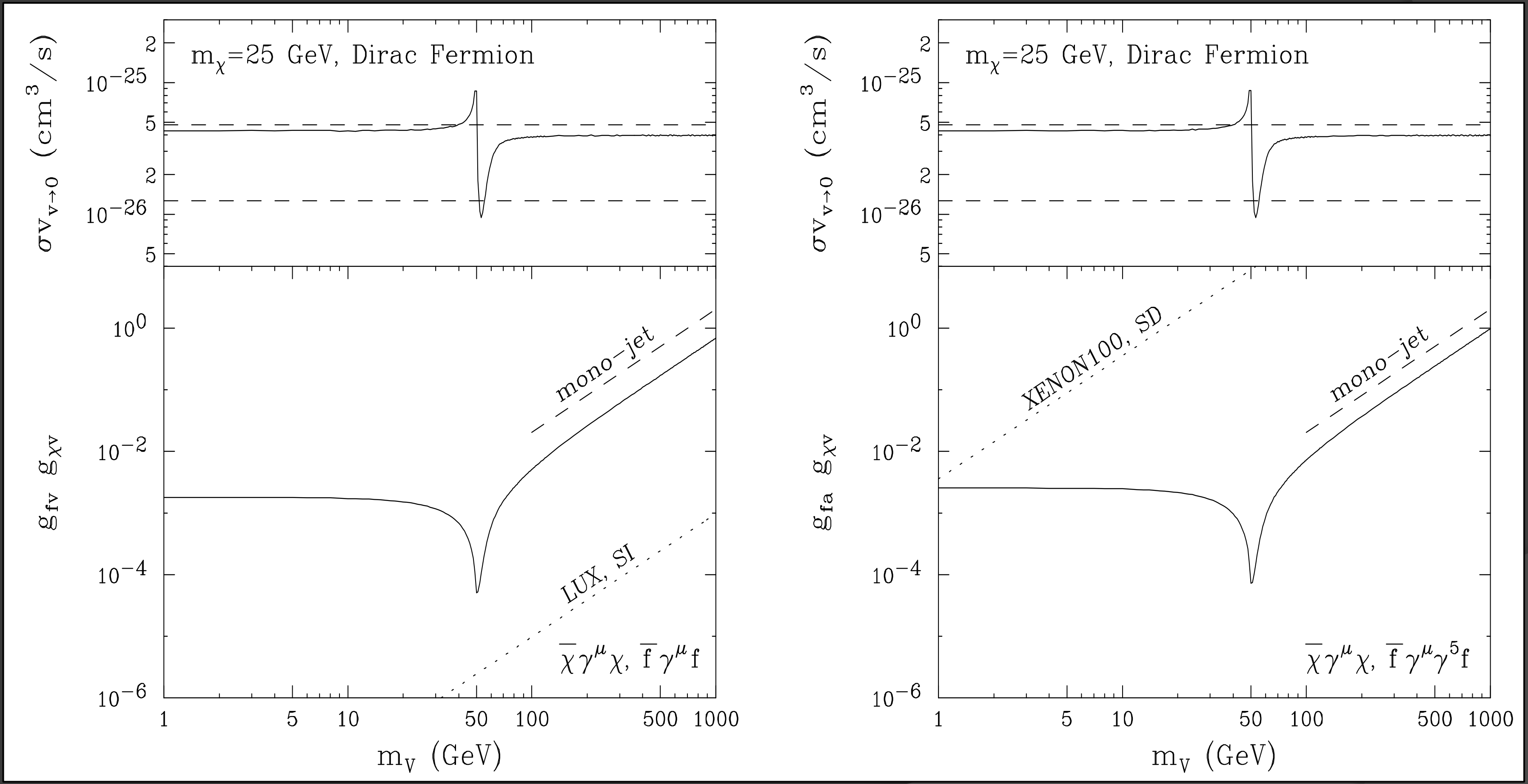
-Models with velocity suppressed annihilation cross sections cannot account for the gamma-ray excess

-Models with unsuppressed vector or scalar interactions with nuclei are ruled out by direct detection constraints

Berlin, DH, McDermott,1404.0022

What kind of WIMP could produce this signal?

Shown another way (for a couple of examples):



Berlin, DH, McDermott,1404.0022

What kind of WIMP could produce this signal?

In general, we find:

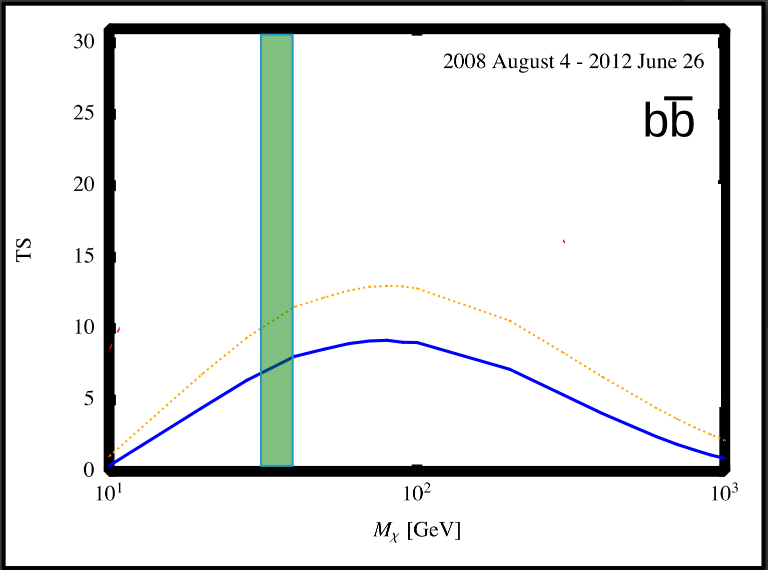
It is not difficult to write down dark matter models with a ~30 GeV thermal relic that can produce the gamma-ray signal in question (satisfied for a wide range of s-wave interactions)

Direct detection constraints rule out models with unsuppressed scalar or vector interactions with quarks

Somewhat contrary to conventional wisdom, the LHC does not yet exclude many of these models (although the 14 TeV reach is expected to be much more expansive)

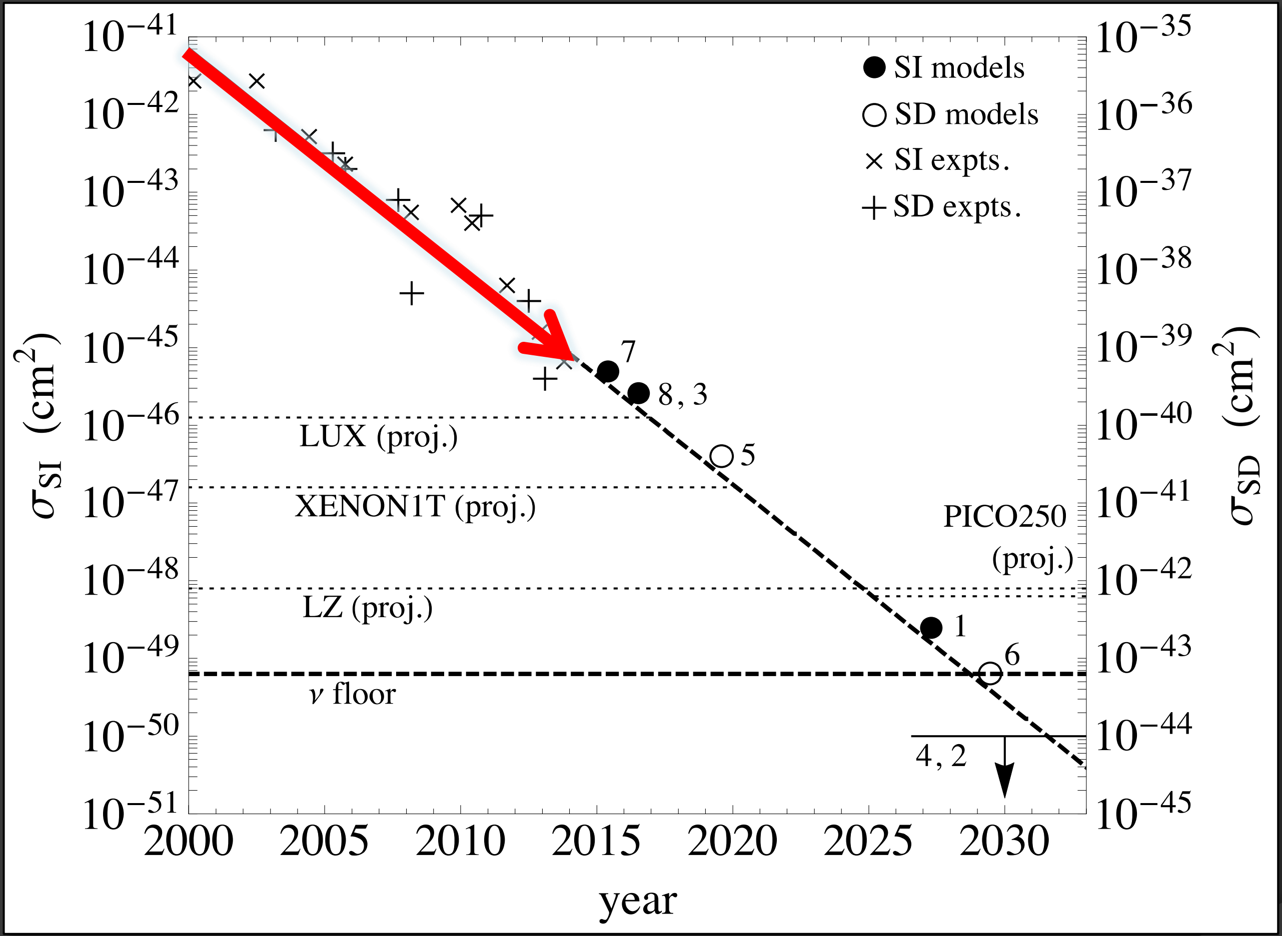
Galaxy Clusters

- Galaxy clusters are also promising targets for indirect dark matter searches, competitive with dwarfs galaxies
- Two groups have reported a gamma-ray excess from the Virgo cluster, at the level of ~2-3σ
- The results of these analyses depend critically on the treatment of point sources and diffuse cosmic ray induced emission, making it difficult to know how seriously one should take this result
- If the excess from Virgo arises from dark matter annihilation, it also suggests a similar mass and cross section that that implied by the Galactic Center excess (up to uncertainties in the boost factor)
- Again, more data should help to clarify

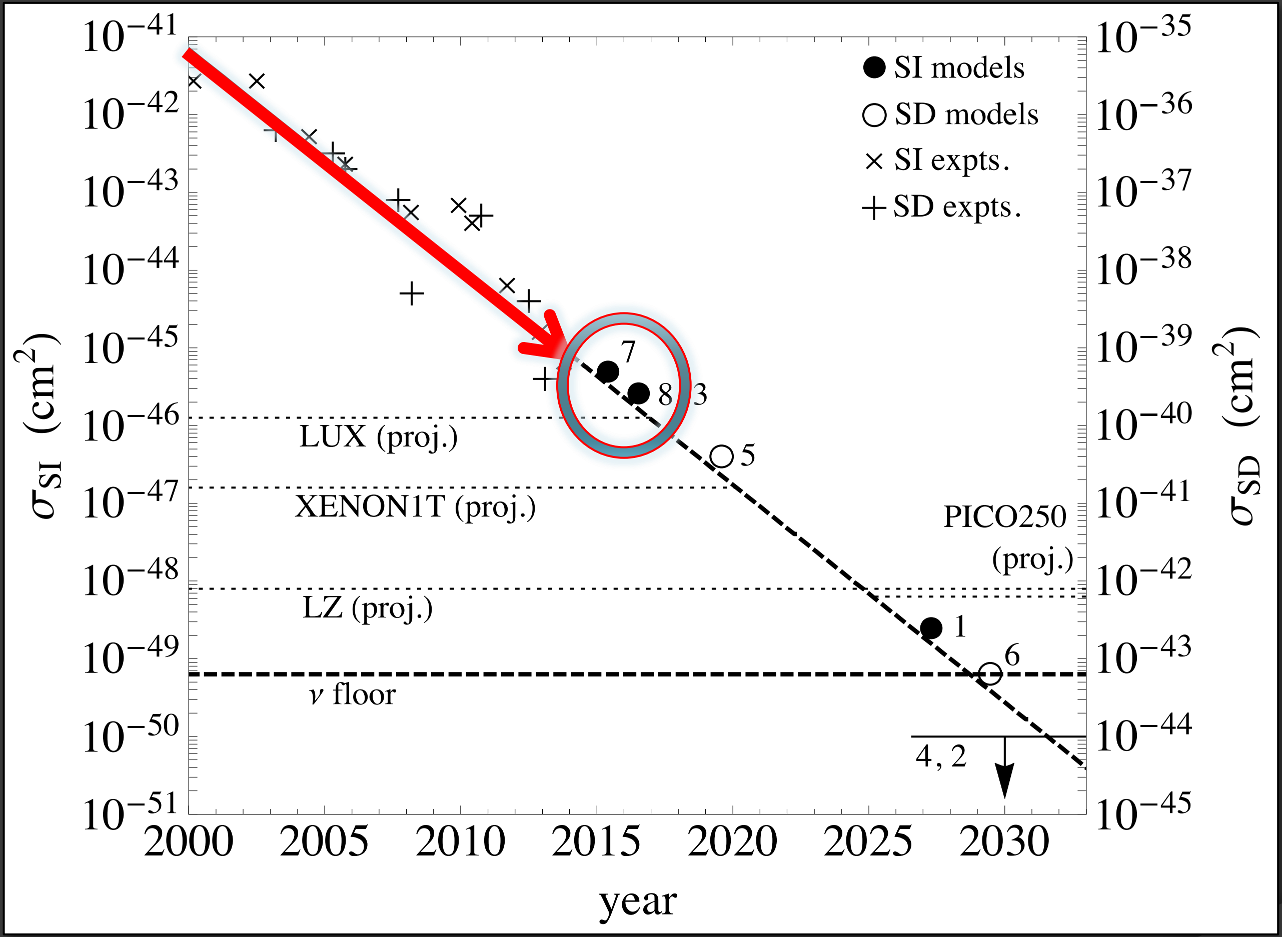


Han, et al., arXiv:1207.6749; Macias-Ramirez, Gordon, Brown and Adams, arXiv:1207.6257

Prospects for Direct Detection

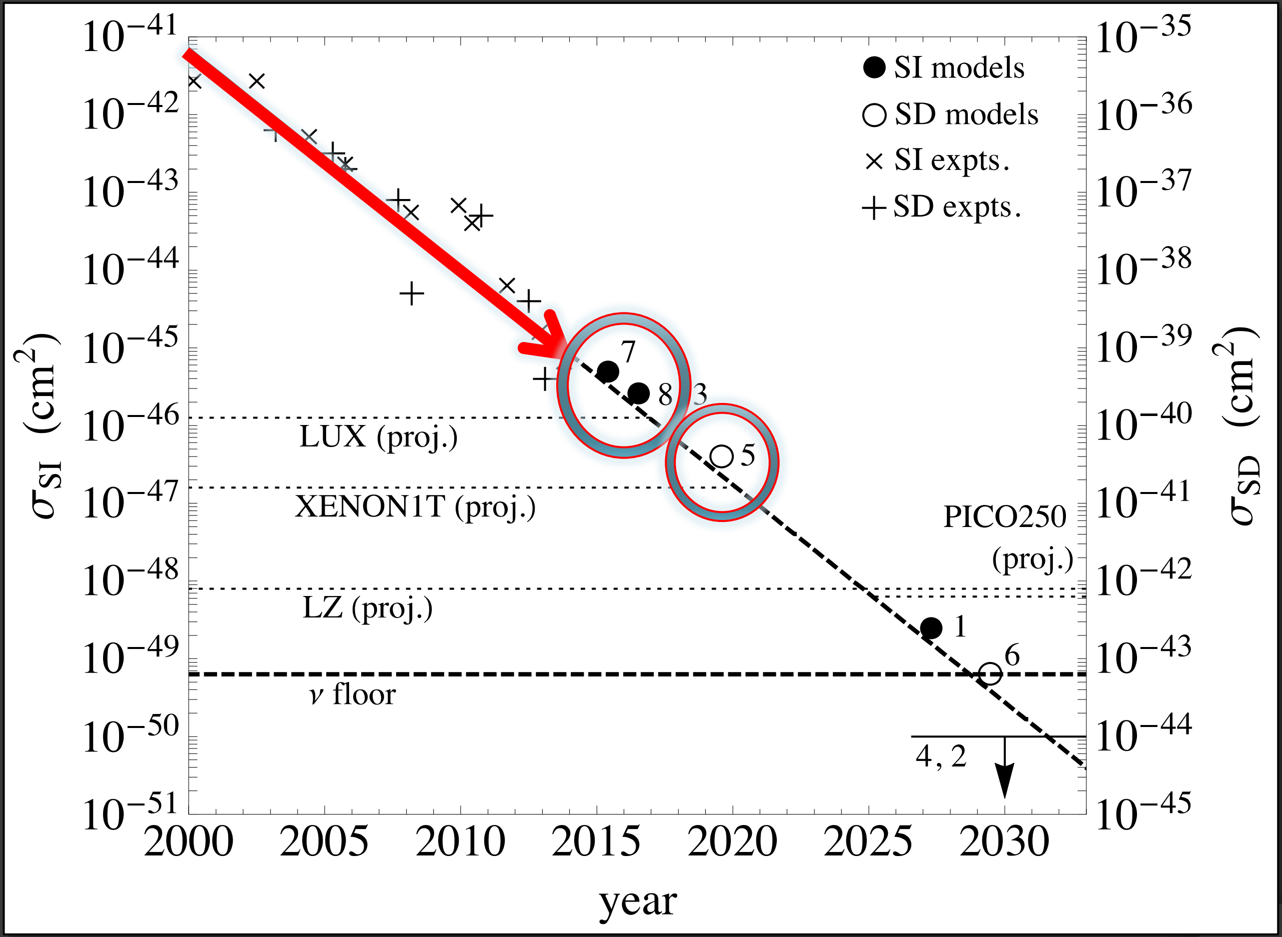


Prospects for Direct Detection



t-channel models are within the reach of both LUX and LHC14

Prospects for Direct Detection



t-channel models are within the reach of both LUX and LHC14

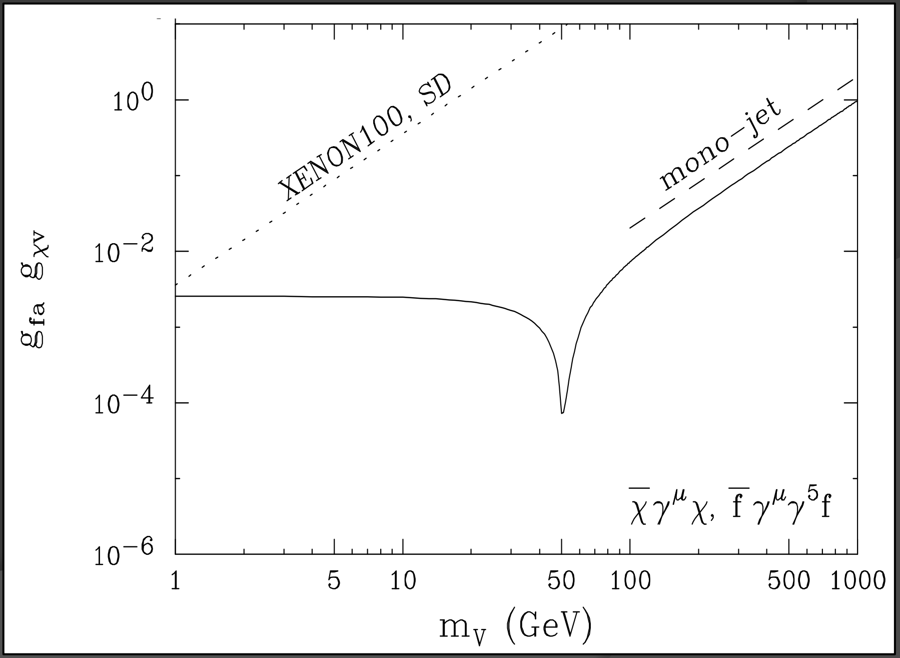
Models with purely axial interactions will be tested by XENON1T

Point 2: It Is Easy To Account For This Signal With Annihilating Dark Matter

The cross section required to normalize the observed excess is remarkably well-matched to the range of values predicted for a simple (s-wave dominated) thermal relic

Direct detection constraints rule out some models (those with unsuppressed scalar or vector interactions with quarks), but many remain viable

Somewhat contrary to conventional wisdom, the LHC does not yet exclude many of these models



Berlin, DH, McDermott,1404.0022

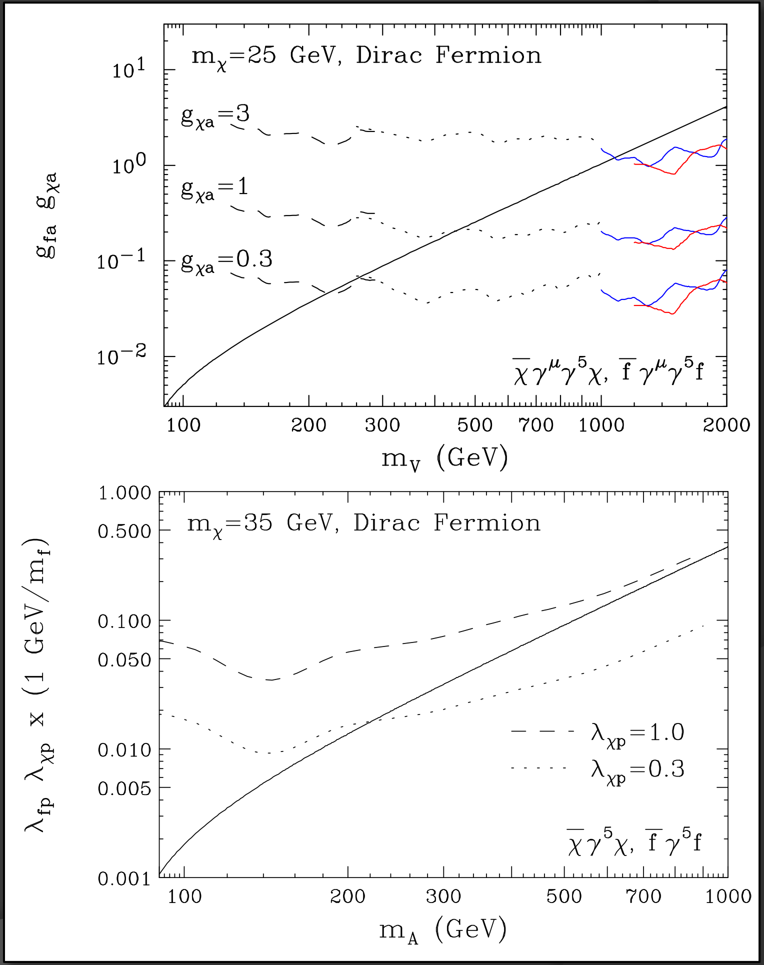
Mediator Constraints

The LHC (and other colliders) can also place direct constraints on the production of particles that might mediate the dark matter's interactions

1) Spin-1 mediators with the required couplings are all but ruled out by Z' searches if their mass is greater than ~1 TeV (lighter and less coupled mediators are more easily hidden)

2) Constraints on MSSM-like Higgs Bosons can be applied to other spin-0 mediators, ruling out a range of masses and couplings

3) Searches for sbottom pair production rule out t-channel mediators lighter than ~600 GeV



A. Berlin, S. McDermott, DH, 1404.0022